VOLUME 20, 1958/59, No. 11 pp. 309-348 Published 21st September 1959

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

MODERN ACOUSTICAL ENGINEERING

I. GENERAL PRINCIPLES

by D. KLEIS.

534.86:534.84:621.395.623.8

*The electrical reproduction of music and speech has been raised to such a high standard in recent years that even practised and critical listeners are scarcely able to distinguish between the reproduction and the original. This was a condition that had to be fulfilled before electro-acoustical methods could be applied to improve the acoustic deficiencies of auditoriums. In this connection it was noted three years ago in this Review as an important milestone in the development of electro-acoustics that leading musicians not only permit microphones and loudspeakers and all that goes with them in the concert hall, but actually welcome their help in making the hall more "playable" *). Since this was written "loudspeakers and all that goes with them" have come into use in numerous concert halls and theatres, including such renowned ones as the Scala in Milan, and the Théâtre National Populaire in the Palais de Chaillot, Paris. It has even happened that performances in acoustically poor halls have been made conditional upon such an installation being in operation.*

In part I of his paper, printed here, the author deals with the principles of acoustic installations both for the amplification of sound and the improvement and control of auditorium acoustics. Some practical installations will be described at greater length in part II.

Electro-acoustical engineering has made great strides in recent years. There have been marked improvements in microphones, amplifiers and loudspeakers, whilst magnetic recording, long-playing gramophone records and frequency modulation have provided novel and better means of recording and transmitting sound. As a result it is now possible to reproduce both music and speech in their original spectrum of frequencies, with virtually their full dynamic range and without troublesome noise. This implies that the equipment used must not only be of high quality, but must also be suitably adapted to its purpose and be operated by properly trained personnel. In practice, when the reproduction is not perfect, it is all too often due to shortcomings in one of these requirements.

The spectrum and the dynamic range, however important, are not the only factors governing the total impression received from the reproduced sound. Where grouped voices or musical instruments are concerned, their spatial configuration plays a considerable part. With *stereophonic reproduction*, employing two or more separate sound channels, full justice can be done to the movement of actors across a stage, the lay-out of an orchestra, etc. [1]). The impression created is far more lifelike than if only one sound channel were used, no matter how good its quality. It has been demonstrated that even critical listeners are scarcely able to distinguish, if at all, between "live" music and its stereophonic reproduction in the same hall [2]).

Modern electro-acoustical devices make it possible not only to unobtrusively reinforce speech or music in the performance of a play or opera (e.g. in a large auditorium or in the open air), but even to relay the speech or music entirely by means of a stereophonic installation without the audience being aware of it. The way now lies open to liberate performances from the restrictions imposed by the size and fitments of the stage. The actions thus become much more natural and the audience gets a greater sense of participation. This can best be illustrated with some examples.

---

*) Philips tech. Rev. **17**, 265, 1955/56.

[1]) See Philips tech. Rev. **17**, 173 et seq., 1955/56, and the literature referred to there.

[2]) R. Vermeulen, A comparison between reproduced and "live" music, Philips tech. Rev. **17**, 171-177, 1955/56.

In plays and operas an actor who is not a musician often has to appear to be playing a musical instrument. He then mimes the actions whilst the actual music emanates from the orchestral pit or from the wings. The audience is usually only too well aware of this artifice either because the sound comes from the wrong direction or because its quality or timbre is not what was expected. However, if the music is played into concealed microphones and the stereophonic sound "image" arranged to move with the actor, the illusion can be well-nigh perfect. A variant of this method is to record the music stereophonically beforehand and to play it back during the performance, letting the actor follow the sound image.

To produce certain effects in operas it is sometimes necessary to have musicians or a chorus concealed in or behind the wings. Quite apart from the unsuitable acoustics of the wings for such a purpose, it is in any case impracticable on a small stage, and even on a large stage the musicians and choristers can hinder the exits and entrances of the other artists. It is much better to make a tape recording of the choral or instrumental music and to play back the tape during the performance. Moreover, electro-acoustical techniques make it possible, if desired, to create the illusion of a much larger chorus. For musical instruments or off-stage sound effects the loudspeakers can be installed in the wings. Such sound effects as footsteps, the roar of cannons, a thunderstorm and rain can be far more impressive when they are played back from a carefully recorded tape than when they have to be created afresh for every performance with acoustically ill-adapted equipment of limited scope.

Another great advantage of producing sound effects electro-acoustically is that the effects need not be confined to the area of the stage. Crowd noises for example, can be made to surround the audience, clarion calls to sound from the back of the hall, thunder and rain to be heard from above. The same sounds can also be made to move through the auditorium stereophonically. With "panoramic sound" and "travelling sound", as these techniques are called, very striking effects can be achieved. The audience is caught up in the action and is given the sensation of participating in it.

These examples should suffice to show how much a stage performance can gain in scope and forms of expression from the support of a good electro-acoustical installation.

So far our remarks have been confined to stage and orchestral performances and to the support lent to them by electro-acoustical techniques. The impression made by a performance, however, is not determined solely by the programme and the method of rendering it, but also to a considerable extent by the acoustics of the auditorium. A speech and a play lose much if they are heard in a hall where reverberations mar intelligibility, whereas an orchestral work played in a hall where the reverberation is excessively damped lacks the fine full tone it acquires in a properly designed concert hall. The high quality of modern sound-reproduction now makes it possible to use electro-acoustical techniques for improving the acoustic properties of halls. There are widespread needs in this respect. There are still many halls in use whose acoustics are quite unsuitable for their purpose. Structural alterations may in some cases provide a solution, but this is not always possible because of the architectural or historic value of the building; moreover it will generally be very much more costly and take longer than installing the electro-acoustical equipment necessary to effect the improvement. There need be no aesthetic objections to the presence of microphones and loudspeakers, since they can be unobtrusively mounted and often completely concealed.

More frequently it happens that the same hall is required to serve for performances of widely different kinds, e.g. for plays, operas, orchestral concerts, etc., each of which make their own demands on the acoustics of the auditorium. This is especially the case in small towns where it is financially out of the question to run a theatre as well as a concert hall. But even in large towns the problem of conflicting acoustic requirements is certainly not unknown; as will appear in part II of this article, there are opera houses that also serve for the performance of symphony concerts, and theatres where organ recitals are given, and so on. The acoustics of such auditoriums should obviously be variable. The non-electrical means available — for example, reversible wall panels which are acoustically hard on one side and sound-absorbent on the other — are costly and in any case never produce really satisfactory results. Electro-acoustically, on the other hand, the acoustics of an auditorium can be varied very much more simply, quickly and efficiently, making it possible to create the acoustic conditions most suited to a wide variety of purposes.

A system of variable acoustics offers particular advantages for the performance of plays and operas, in that it allows the acoustics to be adapted at any given moment to the scene being enacted. During a church scene, for example, the auditorium can be given the acoustic properties of a large church. The audience then not only sees the spectacle on the stage but receives the suggestion that it is itself seated in the church depicted.

In the hands of a good producer this system can provide a perfect synthesis of the illusions created by the play, the decor, the lighting and the sound. As a result the audience can share as never before in the action on the stage, and the performance itself is freed from the restrictions normally imposed by the stage and the auditorium. To this end trained operators are required who can manipulate the apparatus expertly to call forth the effects sought by the producer. During the performance the operators must of course adhere strictly to the scenario as established by the producer during the rehearsals.

In halls whose acoustic properties are unsuitable for musical performances the musicians cannot properly appraise their own playing nor can they hear sufficiently that of their fellow members of the orchestra. Electro-acoustics can effect a considerable improvement in both respects. The result is a "more playable" hall and a better orchestral performance. This is certainly no less important than improving the acoustics of the hall itself.

Installations for improving auditorium acoustics but which are not intended for producing sound effects may often be very large and technically elaborate but their operation should be simple enough to be entrusted to the technicians normally employed in the building. The operations should not entail more than switching the apparatus on and off, routine checking and setting a selector switch to a position corresponding to the type of performance (stage play, opera, chamber music, symphony concert, organ recital). The task of adapting the technical devices to the nature of the hall and to the requirements of the theatre — a task calling for a great deal of skill and experience — rests with the installation engineers.

The Philips Theatre in Eindhoven and the "Gebouw voor Kunsten en Wetenschappen" at the Hague were the first theatres to be provided with an installation designed to make the acoustics suitable for concerts [3]). Since then Philips have brought out theatrical installations of much wider scope, which serve for controlling the acoustics of the auditorium both for music and speech, and also for producing sound effects. Among the buildings thus equipped are the Scala in Milan, the Palais de Chaillot in Paris and the Grand Auditorium built for the 1958 World Fair in Brussels. These installations further make numerous provisions for the members of the public outside the auditorium, for the artists and for the technical staff of the theatre. Details of the installations will be described in part II of this article.

In the part about to follow we shall discuss the acoustical and technical principes of sound installations. These principles apply not only to systems for the complete control of auditorium acoustics in theatres but equally to the far more numerous systems whose aim is more modest, for example installations for making speech intelligible in churches and auditoriums, and for relaying and reinforcing speech and music in stadiums and at open-air meetings, etc. As an example of an elaborate public address system we shall discuss in part II the installation in the "Volkswagen" factory at Wolfsburg.

First of all some general comments. The guiding principle when using electro-acoustical techniques to support a performance or to control the acoustics of an auditorium should be that the electro-acoustical nature of the sound must never be obtrusive. Whether it be a simple speech-reinforcement system or a complex theatrical installation, electro-acoustics achieves its highest success when the acoustical excellence of a performance is attributed to the performance itself and to the acoustics of the auditorium. One prerequisite is that the electro-acoustical equipment employed should be of the highest quality. It is equally necessary, however, to take account of the properties of hearing (the last link in the chain from sound generation to sound perception) and of the laws of auditorium acoustics. We shall therefore preface our discussion of acoustical engineering proper with a brief treatment of these two subjects.

Some properties of hearing

Pitch and loudness

The subjective properties *pitch* and *loudness* are logarithmically related to the physical quantities frequency and intensity of the sound. This logarithmic relation forms the basis for expressing these physical quantities in terms of octaves and decibels [4]). Loudness is not solely determined by the intensity of the sound, however, but also by its frequency. This characteristic of hearing can be expressed in so-called *equal loudness contours*. An equal loudness contour is a curve of sound intensity (dB) as a function of frequency (*fig. 1*) whereby all points on the curve are of equal loudness (phons). At low frequencies the contours are virtually horizontal when the sound intensity is high, but show a marked slope when the intensity is low. This indicates that the timbre of reproduced speech or music will depend on the volume with which it is reproduced. The ear is highly sensitive to such variations in timbre, and therefore correct adjustment of the volume is essential to the lifelike reproduction of sound [5]). In practice this rule is all too frequently violated, usually by the volume control being turned up too high. The inevitable result is an unnatural timbre, owing to the accentuated loudness of the low notes. Moreover, the sound is not made more but less intelligible because the loud low notes mask the high notes necessary for intelligibility. This sometimes leads to unjustifiable complaints about installations which are not themselves at fault but are wrongly operated.

---

[3]) R. Vermeulen, Stereo-reverberation, Philips tech. Rev. 17, 258-266, 1955/56.

[4]) R. Vermeulen, Octaves and decibels, Philips tech. Rev. 2, 47-56, 1937.

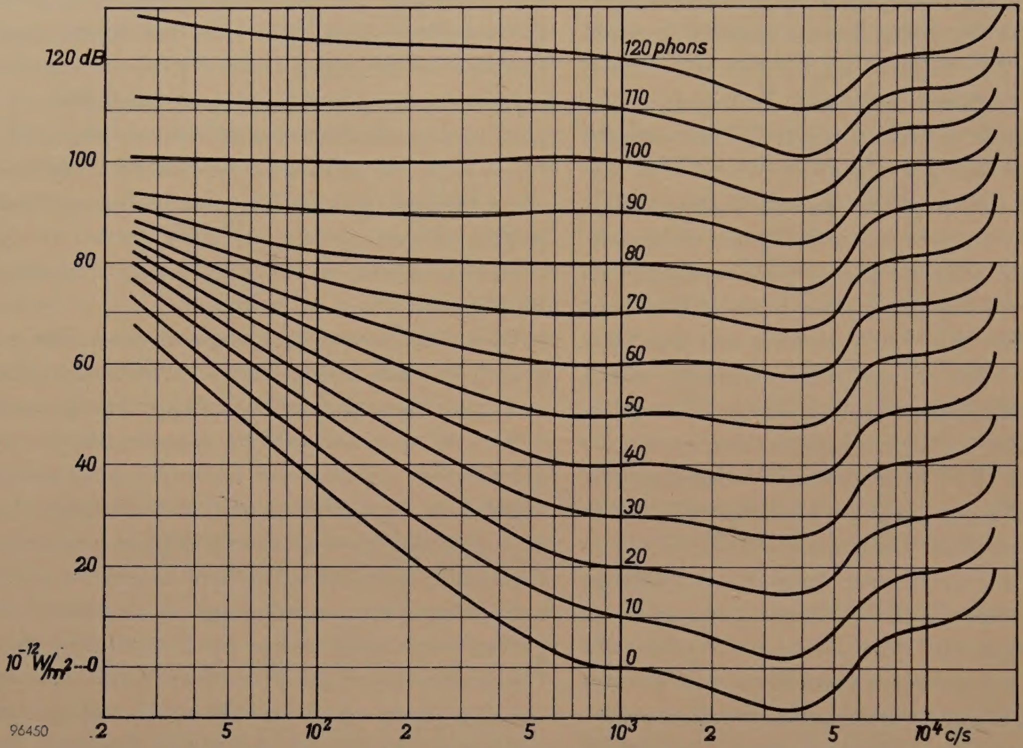


Fig. 1. Equal loudness contours, i.e. curves of sound intensity (in dB above 10^{-12} W/m^2) for constant loudness level (in phons) as a function of frequency. The contour at 0 phon is the threshold of hearing. At low frequencies the contours run roughly horizontal when the sound level is high, but slope sharply when the level is low. (After H. Fletcher and W. A. Munson, J. Acoust. Soc. Amer. 5, 82, 1933.)

In cases where the loudness has to exceed the natural level, owing for example to ambient noise, the low notes should be appropriately attenuated in order to restore the balance between low and high notes. Conversely, where the loudness must be lower than the natural level — e.g. when playing orchestral music in a small room — the low notes should be correspondingly boosted ("low note compensation").

Binaural location

Another important auditory property is the ability to hear the direction from which a sound comes. We shall first consider the case of an observer listening to a sound source in the open air. The sound from a source which is mounted at head-height outside the plane of symmetry of the head is not received equivalently by both ears. The ear turned more towards the source receives the sound earlier and in greater intensity than the other ear which the sound reaches only after bending around the head. The more lateral the position of the source with respect to the ears the more will the sounds reaching the two ears differ in time of arrival and in intensity. Binaural location depends primarily on the *intensity* differences, especially in the high notes since these are strongly screened by the head, whereas the low notes are less screened and reach both ears with almost equal loudness. The direction of low notes thus cannot be judged precisely. In a stereophonic system, therefore, the notes below 300 c/s are sometimes not reproduced via two channels but via one only, so that only one bass loudspeaker is required.

---

[5]) In the comparative experiments discussed in article [2]) particular care was therefore taken to ensure that the reproduced music was just as loud as the live music.

In an enclosed space the ears are virtually unable to locate the sound if it consists of a sustained note. The ears are then at different positions in a standing wave pattern and so perceive marked differences that have nothing to do with the direction of the sound source. On the other hand, if the sound is suddenly switched on, its location is easily determined since the first sound to reach the ears already reveals the direction from which it came before the pattern of standing waves is built up. Sounds with frequent transients (speech, percussion instruments) are thus most readily located by the ears.

So far we have considered directions in the horizontal plane at ear height. The elevation of a sound source is much more difficult to detect aurally, inasmuch as it is perceived indirectly through slight unconscious movements of the head [6]). Visual indications can strongly influence the aural perception of elevation. As cinema projection screens got bigger and wider the need was felt for some means of making the sound move horizontally with the visible source on the screen, but never vertically, because of the difficulty of perceiving elevation.

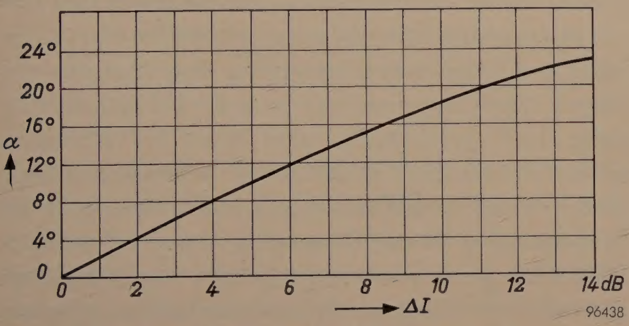


Fig. 2. Angular displacement α of the stereophonic sound image from its midway position as a function of the difference in intensity ΔI between the two loudspeakers.

Binaural hearing, then, makes it possible to locate the direction of a single sound source and to perceive the spatial distribution of a number of sound sources (auditory perspective). The latter gives orchestral music a certain transparency, in that the ears can distinguish spatially between the instruments. This is not possible monaurally, nor if the music is heard reproduced via a single channel.

Stereophony

When two loudspeakers are set up a certain distance apart and reproduce simultaneously the same sound with equal intensity, a listener at the same distance from both loudspeakers does not hear two sound sources but only one, and this virtual "sound image" is located midway between the two loudspeakers. If one of the loudspeakers radiates the sound earlier or louder than the other, the sound image is perceived to be closer to the first loudspeaker. A lead in time of three milliseconds or an intensity preponderance of 15 dB shifts the sound image fully to the first loudspeaker; smaller differences in time and intensity produce, independently and additively, proportionally smaller displacements; see *fig. 2* and *fig. 3* [7]). Displacements due to a time difference can be corrected by applying a certain intensity difference; in *fig. 4* it is shown that an intensity difference of 5 dB corresponds to a time difference of 1 millisecond.

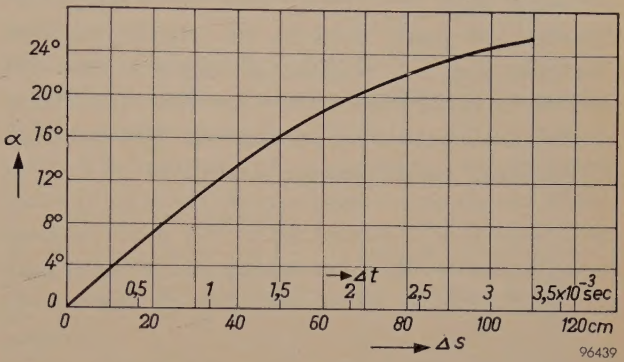


Fig. 3. Angular displacement α of the stereophonic sound image from its midway position as a function of the time difference Δt between the sound from the two loudspeakers. (Δs is the corresponding difference in the distance travelled by the two contributions.)

The auditory property causing two sounds to merge into a single sound image, whose location within the limits mentioned is determined by the differences in the time of arrival and intensity of the two sounds, constitutes the basis of stereo-

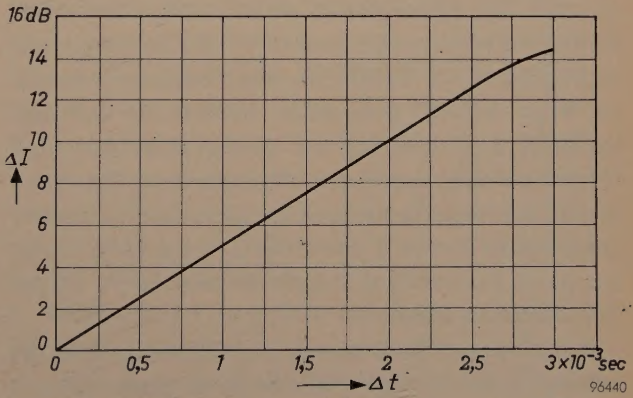


Fig. 4. For each time difference Δt, the intensity difference ΔI is plotted which causes the same angular displacement of the stereophonic sound image.

---

[6]) K. de Boer, A remarkable phenomenon with stereophonic sound reproduction, Philips tech. Rev. **9**, 8-13, 1947.

[7]) K. de Boer, Stereophonic sound reproduction, Philips tech. Rev. **5**, 107-114, 1940.

phonic reproduction. With a suitable arrangement of two microphones connected via separate channels to two loudspeakers (*fig. 5*) the sound sources in front of the microphones are imaged between the loudspeakers. In this way the sound image of speech or music can be arranged to lie at an arbitrary position between the loudspeakers. Moreover the sound image can be shifted by introducing from a control desk appropriate time or intensity differences, or both, between the signals in both channels. This is a familiar technique in film studios for making films with more than one sound track, and is known by the name of "pan potting" ("panoramic potentiometer control").

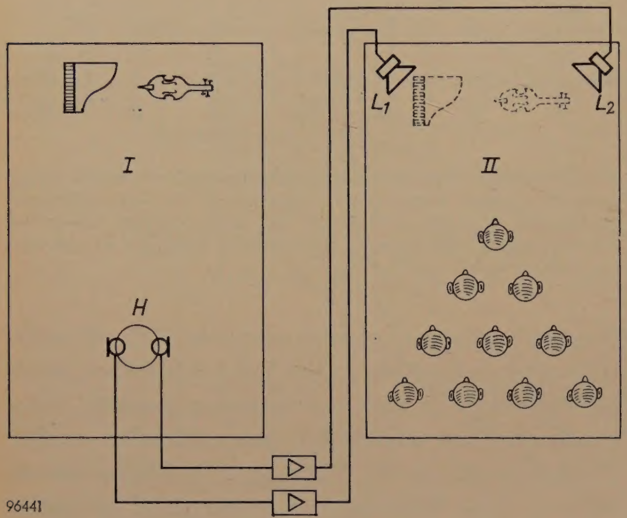


Fig. 5. Stereophonic transmission of music. The microphones on an artificial head *H* in room *I* are connected via separate channels to loudspeakers L_1 and L_2 in auditorium *II*, where the audience receives stereophonically an impression of the spatial disposition of the musical instruments.

If the listener is not equidistant from the two loudspeakers the result is an additional time difference due to the difference in distance. Consequently the stereophonic sound image shifts towards the loudspeaker nearer to the listener. In a large part of an auditorium this displacement can be kept within reasonable bounds by suitably disposing and directing the loudspeakers (we shall return to the latter point presently). By these means it is possible to produce intensity differences that depend so much upon the position of the listener as to compensate largely for the effect of the differences in distance.

Where sound from two loudspeakers reaches the listener with a time difference of more than 3 milliseconds, the sound is heard to be issuing from that loudspeaker whose sound was first received; even if the intensity from the other loudspeaker is increased, the sound image can no longer be displaced. For such a listener, the stereophonic character of the reproduction is absent. Where the time difference is about 20 milliseconds the delayed loudspeaker can be made 10 dB louder than the other before the listener is aware that sound is issuing from it at all. Nevertheless, the delayed loudspeaker does influence the quality of the sound, which is thereby made not only louder but also fuller in tone.

Where the time difference is greater than 50 milliseconds, the sound last to arrive is heard separately as a disturbing echo, unless it is 10 or more decibels weaker than the preceding sound.

The fact that sound arriving with a delay of about 3 to 50 milliseconds is aurally merged with the preceding sound, and is also heard to issue from the direction of the preceding sound, can be utilized for electrical sound-reinforcement in order to amplify speech, for example, by up to 10 dB, in such a way that the listeners are not aware of the electro-acoustical aids employed. They hear the sound apparently coming from the speaker, even though the loudspeaker sound comes from a different direction.

The above auditory properties make directional hearing possible in an auditorium spite of the fact that most of the sound reaches the listeners after reflection from the walls, hence from directions other than that of the sound source. The reflected sound waves travel a circuitous path through the auditorium and thus always reach the listeners later than the sound waves travelling directly from the source. The delays suffered by reflected sound in a large hall, particularly after multiple reflections from the walls, far exceed the above-mentioned time difference of 50 milliseconds, which corresponds to a distance of about 17 metres. Nevertheless, in a hall with good acoustic properties the reflections are not heard separately but together as a reverberation. The ear distinguishes individual reflections only where they stand out above the general level of sound and are also delayed by at least 50 milliseconds. If they are part, however, of a succession of reflections each following within 50 milliseconds of each other, they are not heard individually.

To recapitulate, then, there are three cases to be distinguished in the reproduction of sound via two loudspeakers:

1) Where the sounds follow within 3 milliseconds of each other, they merge to form a single stereophonic sound image whose position between the loudspeakers is determined by the difference in the time of arrival and intensity of the two sounds.
2) Where the interval between the sounds is between approximately 3 and 50 milliseconds, the

sound first to arrive determines the direction; the delayed sound influences the loudness, however, and also the quality of the sound, inasmuch as it created a more spatial impression.

3) Where the interval between the sounds is greater than 50 milliseconds, the sound last to arrive is generally heard as a troublesome echo, unless it is at least 10 dB weaker than the preceding sound.

The first and second cases apply to sound reproduction and to the performance of music in an acoustically suitable auditorium. The third case applies to acoustically unsuitable auditoriums, e.g. where there are "flutter echos" between parallel walls and troublesome reflections from the rear wall. In electro-acoustical installations these conditions should be avoided at all costs by appropriate arrangement of the loudspeakers.

Auditorium acoustics

The correct application of electro-acoustical techniques implies taking into account not only the properties of hearing but also the behaviour of sound in the open air and in enclosures.

We have seen that the listeners in a hall receive the sound only to a minor extent from the source ("direct sound") and for the most part via reflections from the walls ("indirect sound"). Consequently speech and music sound much louder in an enclosed space than in the open air, where the virtual absence of reflections means that only direct sound is received.

Direct sound is characteristic of the sound source itself. It represents the information conveyed and the artistic merit of the performance. By virtue of his aural sense of direction the listener is able to perceive in the direct sound the spatial distribution of an orchestra, the movement of actors over the stage, and so on. It follows, then, that faithful sound reproduction requires that the loudspeakers should radiate the direct sound with its original spectrum, its full dynamic range and stereophonically.

Indirect sound, although of course it originates from the same source, is primarily characteristic of the acoustic properties of the auditorium. It differs from direct sound in three ways.

In the first place indirect sound does not issue from one specific direction but from all directions in the auditorium. Unlike direct sound which is localized, indirect sound is therefore diffuse, and becomes all the more so the more effectively the walls disseminate the sound in all directions (i.e. reflect it diffusely) and the less they absorb it. In order to reflect sound diffusely the walls must be rough. The roughness should be considered in relation to the wavelengths of the sound. These vary from a few metres for the low tones to a few centimetres for the high tones. From the viewpoint of diffuseness the old concert halls with their wealth of ornamentation are more favourable than modern concert halls the walls of which are generally much plainer. It is particularly unfavourable if the sound is converged upon certain points in the auditorium in consequence of the shape of the walls. This can give rise to annoying echos.

Since the indirect sound is diffuse its intensity will be roughly the same everywhere in the auditorium. The intensity of direct sound, on the other hand, is inversely proportional to the square of the distance from the sound source. The proportional intensities of the direct and indirect sound gives the listener an indication of his distance from the source.

The second difference between the two kinds of sound is that, in travelling to the listener via the walls, the indirect sound always arrives later than the direct sound. This delay is relatively slight as far as the reflections from the rear wall of the stage or platform and from the floor are concerned; these reflections come from virtually the same direction as the direct sound. The reflections from other areas will be more delayed the larger is the auditorium. As explained above, a very slight delay in reflected sound is sufficient to eliminate its influence on the directional perception of the direct sound. Owing to the delay the perception of the direct and the indirect sound differs, and the listener perceives in the latter a greater or lesser diffuseness.

The third difference between direct and indirect sound is that, when the source stops radiating, the direct sound ceases at virtually the same instant, whereas the indirect sound persists for a time that depends on the degree to which the sound is absorbed every time it strikes a wall. Apart from being absorbed in the walls, the sound is attenuated — the high frequencies more than the low — on its way through the air, particularly as a result of atmospheric impurities (moisture, carbon dioxide, smoke). The less the absorption the greater will be the intensity and diffuseness of the sound and the longer will it take before it dies out.

These related properties are characterized by the reverberation time of an enclosure, which is defined as the period of time required for the sound to decrease, after the source is stopped, to one millionth of its initial intensity, i.e. by 60 dB; in practice this amounts to the time taken for the sound to become inaudible. The reverberation time is found to be proportional to the volume of the enclosure and inversely proportional to the total equivalent absorption (Sabine's law) [8]). The unit of equivalent absorption is the "sabin" equal to the absorption of one square foot of a surface which absorbs *all* the incident sound energy. In the metric system this is given in the number of m^2 "open window"; a surface of 2 m^2 having an absorption coefficient of 0.1 contributes 0.2 m^2 "open window" to the equivalent absorption.

In general the reverberation time increases with the size of the enclosure, since the volume increases more rapidly than the surface of the walls. Measurements carried out in numerous auditoria with good acoustic qualities have provided sufficient data to make it possible to determine the optimum reverberation time for enclosures of various volumes and intended for different purposes (*fig. 6*).

Since the absorption coefficients of the various materials used for covering the walls are functions of frequency, the reverberation time of an auditorium will vary with the frequency of the sound in a way that depends on the materials used. Every auditorium, therefore, lends a distinct timbre to the indirect sound. In this respect there is a great difference between, for example, wooden and stone walls. In a hall with a glass roof or with large windows the reverberation time is short for the low notes owing to the fact that the glass transmits the low notes to a much greater extent than the high. *Fig. 7* shows a plot of reverberation time as a function of frequency for various concert halls. In general the reverberation time decreases towards the higher frequencies, which undergo more absorption in conventional wall materials and are moreover increasingly damped by the air. If *the* reverberation time of an auditorium is quoted, it usually refers to the reverberation time for a frequency of 500 cycles per second.

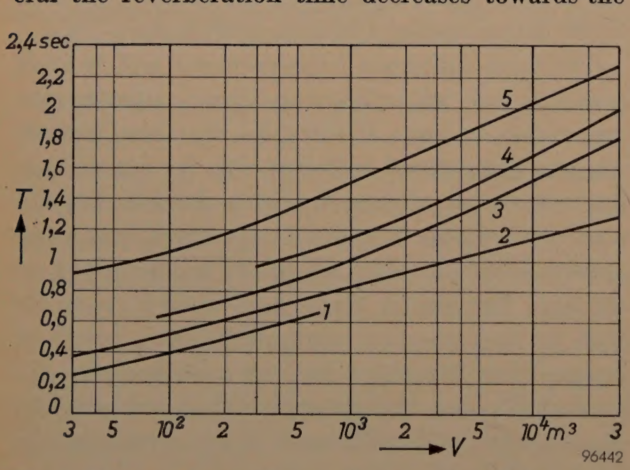


Fig. 6. The most favourable reverberation time T for various auditoria as functions of the volume V of the auditorium (taken from L. L. Beranek, Acoustics, McGraw-Hill, New York 1954). Curve *1*: broadcasting studios for speech. Curve *2*: meeting halls, cinemas. Curve *3*: broadcasting studios for music, opera house auditoria. Curve *4*: concert halls, Protestant churches, synagogues. Curve *5*: Catholic churches, auditoria for organ recitals.

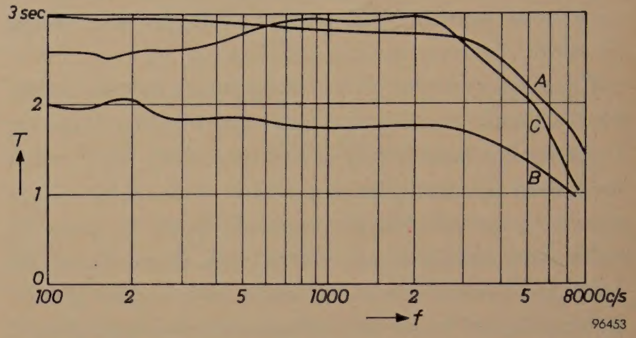


Fig. 7. Reverberation time T as a function of frequency f for various concert halls, after measurements by W. Tak. Curve *A*: Grand Hall of the Amsterdam Concertgebouw. Curve *B*: Philharmonic Hall, Liverpool. Curve *C*: St. Andrew's Grand Hall, Glasgow.

The audience in an enclosure is reponsible for a great deal of sound absorption. To prevent the acoustics depending unduly upon the size of the audience, efforts are made to cover the seats in such a way that, whether occupied or not, they present approximately the same absorption.

Auditorium acoustics for speech and music

The acoustic properties required of an auditorium for speech and for music are quite different.

Speech acoustics require the loudness reinforcement due to the indirect sound but not the reverberation, since this makes the speech less intelligible. As mentioned, the indirect sound arriving within about 50 milliseconds after the direct sound contributes usefully to the loudness and affects neither the impression of direction nor the intelligibility. Sound delayed by more than 50 milliseconds, however, reduces intelligibility in that it overlaps the sounds that follow. To be no longer troublesome the sound delayed more than 50 milliseconds must be made about 10 dB weaker. Theatres and lecture halls are therefore designed in such a way that the reflections arriving with a delay of less than 50 milliseconds are as far as possible directed towards the audience, whilst efforts are made to damp the more delayed reflections by providing the appropriate parts of the walls with absorbent material. For example, the lower part of the rear wall in a theatre will be made acoustically hard so that the audience at the back of the theatre will receive additional useful sound. The upper part of the rear wall, however, will be covered with absorbent material to prevent long-delayed reflections from arriving at the front of the theatre and on the stage. A good theatre auditorium, in which the reflections are properly directed on the audience, has a fairly short reverberation time (0.7 to 1.0 second) and little diffuseness.

---

[8]) See e.g. A. Th. van Urk, Auditorium acoustics and reverberation, Philips tech. Rev. 3, 65-73, 1938.

In a concert hall the diffuseness and the reverberation are essential to give "body" to the music. A symphony orchestra requires a large hall and a reverberation time of 1.8 to 2.5 seconds to be heard at its best. A church organ requires an even greater space and an even longer reverberation time.

The above aspects of auditorium acoustics, on which electro-acoustical control is based, may be summarized as follows:

1) There is a fundamental difference between direct and indirect sound. Direct sound provides the stereophonic impression of what is taking place on the stage or orchestral platform; it gives "definition" to the sound. Indirect sound, with its timbre, diffuseness and reverberation, is characteristic of the auditorium; it invests the sound with spaciousness and gives fullness or body to music, the more so the greater the degree of diffuseness. Where the indirect sound is delayed more than 50 milliseconds, however, it adversely affects the intelligibility of speech.
2) The delay of the indirect sound creates an impression of the size of the auditorium.
3) The relation between the intensities of direct and indirect sound determines the impression of distance.

Electro-acoustical control of auditorium acoustics

The natural direct and indirect sounds heard in an auditorium are correlated by the properties of the auditorium. The possibility of controlling the acoustics of an auditorium results from the fact that the direct and indirect sound can be separately produced and controlled by electro-acoustical means. It is therefore a principle in modern acoustic installations to produce the direct and indirect sound separately through individual groups of loudspeakers.

Direct sound

For producing almost pure direct sound, loudspeakers are used that beam their sound in the direction of the audience, so that as little as possible is incident on the walls. The gain in the ratio of direct to indirect sound obtained by beaming can be demonstrated by the following numerical example.

Consider a large auditorium with acoustically hard walls and a floor sloping up towards the rear, and imagine a speaker in this auditorium who sees his audience within a horizontal angle of 90° and a vertical angle of 15°.

For the notes in the low and medium frequency ranges the speaker can be regarded as a virtually spherical radiator, radiating sound with equal intensity in all directions. A simple calculation shows that the solid angle within which he sees the audience covers only 1/30th of the total solid angle of 4π steradians around the speaker. Thus only 1/30th of the radiated sound reaches the audience directly and 29/30th strikes the walls, which reflect it for the most part as disturbing, reverberant sound. The ratio of direct to indirect sound is thus about 1/30 : 1. Consequently the speaker will be understood well only in the front rows of the auditorium; towards the rear the intelligibility decreases rapidly (*fig. 8a*).

Now imagine the speaker to be replaced by an ideally beamed loudspeaker, i.e. one which exactly comprises the audience within its sharply defined radiating angle. The entire radiated sound will now reach the audience in the form of direct sound. The clothing worn by the audience and the unoccupied, suitably covered seats absorb about 80% of the incident sound (except for the very low notes, to be dealt with presently). The reflected fraction, about 20%, impinges on the walls and is responsible for a certain intensity of indirect, reverberant sound. The ratio of direct to indirect sound is now approximately 5 : 1, that is about 150 times greater than in the first case considered. The direct sound now predominates over the indirect sound right to the back of the hall, and therefore the speech is everywhere perfectly intelligible (fig. 8*b*).

In reality the speaker and the beamed loudspeaker are usually both present in the auditorium, the loudspeaker being used to reinforce the speech which is spoken at a normal level as if no sound installation were there. The indirect sound due to the speaker himself is then, of course, just as loud as it would be if no sound installation were present. As we have seen above, the direct sound from the speaker can be relayed by the loudspeaker amplified 150-fold, before the indirect sound significantly increases; the above-mentioned advantage of beaming can thus in practice be realized almost to the full. In practice a much smaller amplification is found sufficient, particularly if the beam — whose intensity gradually decreases from the centre towards the edges — is directed mainly towards the rear half of the auditorium (fig. 8*b*). The ratio between the

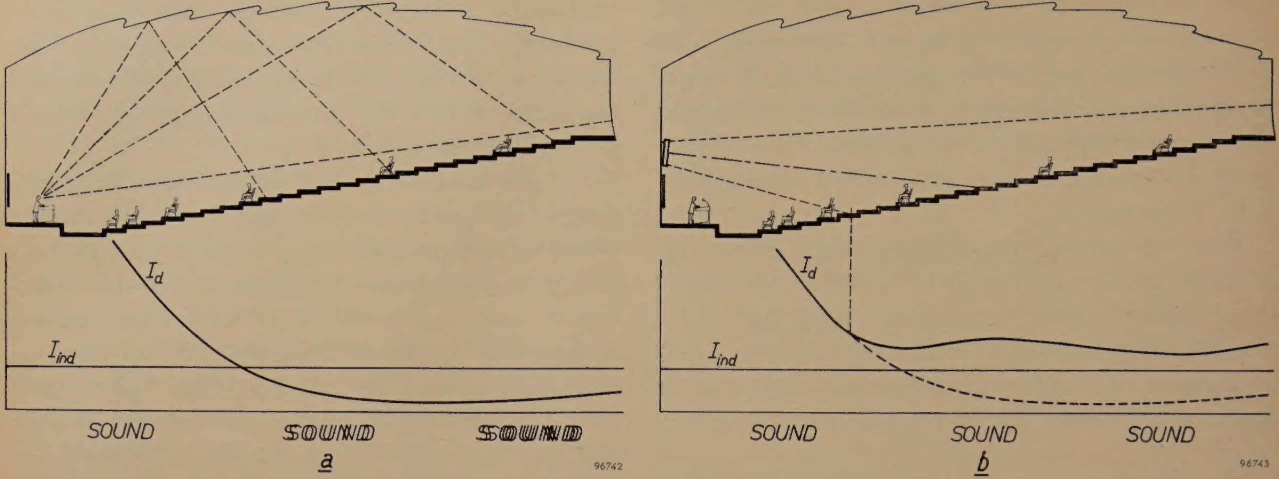


Fig. 8. *a*) A speaker in a large hall having acoustically hard walls (long reverberation time) can be understood by the audience near the front, but towards the rear the intelligibilty is spoiled by the disproportionately strong indirect sound (see the curves showing the sound intensities I_d and I_ind of the direct and indirect sound, respectively, as a function of the distance to the speaker). *b*) By means of a group of loudspeakers which direct the sound mainly on to the rear part of the hall, I_d can be made strong enough in proportion to I_ind to make the speech perfectly intelligible to the whole audience.

intensities of direct and indirect sound can now be virtually the same at all positions in the auditorium and sufficient for good intelligibility, without the audience being aware that they are listening to the loudspeaker. The impression of hearing the speaker directly can be reinforced if the loudspeaker, or loudspeakers, be so arranged that the radiated sound reaches the audience 10 to 20 milliseconds later than the direct sound from the speaker. The impression of direction is just as unaffected under these conditions as it is by the "useful" reflections of less than 50 milliseconds delay in a good auditorium.

It is well known that a beam of sound having a large horizontal and a small vertical radiating angle can be obtained by means of a loudspeaker column (or "sound column"), consisting of several loudspeakers mounted one above the other and all operating in phase (*fig. 9*).

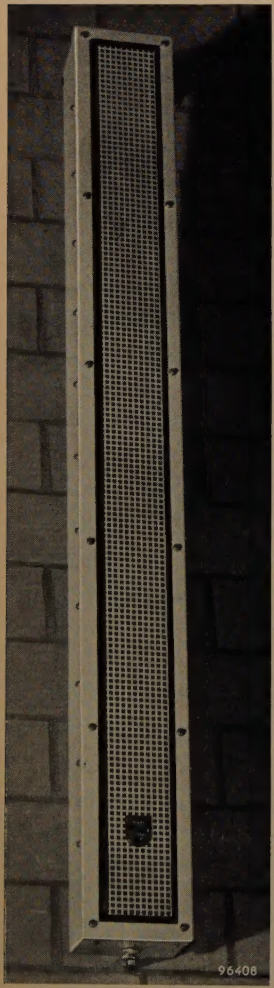


Fig. 9. A loudspeaker column.

The beaming action of a loudspeaker column is based on interference effects between the various loudspeakers. Consider a vertical column and a listener situated in the horizontal median plane of the column at a distance which is large with respect to the length of the column. The sound waves from the various loudspeakers in the column will reach the listener virtually in phase and thus augment each other. Let the column contain n loudspeakers, then the sound pressure and the sound intensity reaching the listener will be respectively n and n^2 times greater than from a single loudspeaker in the column. Since a single loudspeaker is fed with $1/n$ of the power supplied to the whole column, the sound intensity in the beam radiated by the column is n times greater than that of a single loudspeaker fed with the same total electric power.

If the listener moves his position up or down, he is no longer at an equal distance from the individual loudspeakers. He no longer receives all their sound waves in phase; the augmenting effect is therefore diminished and the sound intensity decreases. If his position is so far above or below the horizontal median plane that the distances between him and the top and bottom loudspeakers differ exactly by the wavelength λ (we assume that the loudspeakers radiate only one note), then each loudspeaker above the median plane will have a counterpart half the column length lower whose sound waves arrive at the listener exactly in anti-phase. No sound is therefore radiated in directions where this is the case. The same situation is found where the listener is so far outside the median plane that the distances between him and the top and bottom loudspeakers differ by 2λ, 3λ, and so on.

Between these regions of zero intensity there are regions of maximum intensity (*fig. 10*) which however become progressively smaller than that in the median plane; only in this plane is the sound from all the loudspeakers received in phase. Let the sound intensity in the median plane (the zero-order maximum) be I_0, then the intensity in the k^{th} maximum is:

$$I_k = \left[\frac{1}{(k+\frac{1}{2})\pi}\right]^2 I_0 .$$

The sound radiation can be said to be largely concentrated within the zero-order region. This main lobe covers an angle $2\varphi_0$ given by

$$\sin \varphi_0 = \frac{\lambda}{L},$$

where L is the length of the column. For small values of φ_0 the radiating angle can be written:

$$2\varphi_0 = \frac{2\lambda}{L}.$$

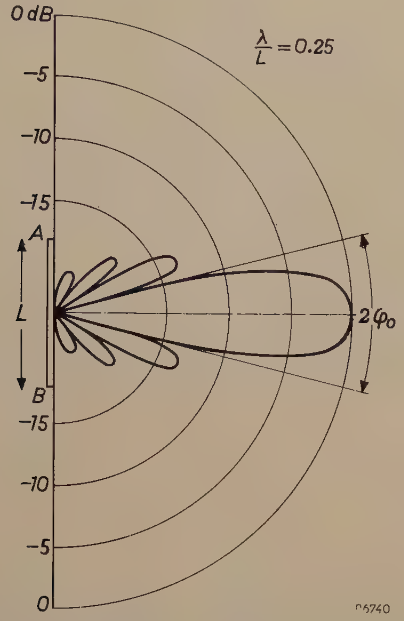


Fig. 10. Directional characteristic of a loudspeaker column AB in the vertical plane of symmetry at a given frequency. Virtually all the energy is radiated in the main lobe, the angle $2\varphi_0$ being smaller the higher the frequency and the longer the column.

The beaming effect of a loudspeaker column in the vertical plane is sharper the longer the column and the shorter the wavelength of the sound (i.e. the higher the frequency). For a column two metres in length the radiating angle at 300 c/s is 68°, and at 3000 c/s only 6.4°. To comprise as many listeners as possible within the narrow beam of the high notes it is therefore necessary to arrange the column so that the beam passes closely over the listeners' heads.

The beaming effect of the column in the horizontal plane does not differ from that of an individual loudspeaker. A single loudspeaker also tends to concentrate the high notes increasingly around the principal axis. Horizontal beaming is usually undesirable since it prevents the proper distribution of the high notes in an auditorium, and it is precisely the high notes that are essential to good intelligibility. To avoid beaming in the horizontal plane it is advisable in the first place to use twin-cone loudspeakers. The response curve of these loudspeakers extends to about 18 kc/s, i.e. to the highest audio frequencies, and the high frequencies are beamed much less sharply than by single-cone loudspeakers [9]). Secondly, the loudspeakers of the column should be mounted with their axes not parallel but with slight angular displacements with respect to each other so that the individual high-note beams uniformly fill the total beam. For the tones in the low and medium ranges the loudspeakers then form a long column with a pronounced directional character, whereas for the higher notes the effective part of the column tends to become more and more limited to those loudspeakers pointing in the listeners' direction; for the very high notes there is only one effective loudspeaker for each point of the auditorium. The reduction of the effective part of the column with increasing frequency thus keeps pace more or less with the shortening wavelengths, resulting in a fairly constant radiating angle.

Below about 300 c/s the directional effect even of a long column is inadequate, and moreover the sound undergoes less absorption by the audience. In this frequency range, then, the indirect, reverberant sound tends to increase. To avoid this it is necessary to attenuate the reproduced low notes by means of an electric filter and/or by fixing the resonance frequency of the loudspeakers in the region of 300 c/s (below resonance the radiated power drops rapidly as the frequency decreases). This relatively high resonance frequency can be obtained either by using a sufficiently small cone or by introducing a small enclosed volume of air behind the cone. The latter method has the advantage of reducing non-linear distortion [10]), a point of particular importance if the loudspeakers have to operate at full power, which is often necessary out of doors. The suppression of the sound spectrum below 300 c/s does not make speech sound any less natural; on the contrary, it restores the balance in that it compensates for the reduced damping of the sound in the auditorium at lower frequencies.

If the column is built up of small loudspeaker boxes, capable of being independently aimed, the column can be of simple construction yet completely adapted to the requirements of the auditorium. In the Palais de Chaillot, columns of this kind are mounted at either side of the stage (*fig. 11* and *fig. 12*). The columns are used for stereophonic speech reinforcement for stage plays and for relaying stereophonic sound effects pre-recorded on twin-track magnetic tape (see part II).

---

[9]) J. J. Schurink, The twin-cone moving-coil loudspeaker, Philips tech. Rev. **16**, 241-249, 1954/55, in particular figs. 9 and 10.

[10]) G. J. Bleeksma and J. J. Schurink, A loudspeaker installation for high-fidelity reproduction in the home, Philips tech. Rev. **18**, 304-315, 1956/57, in particular p. 310-311.

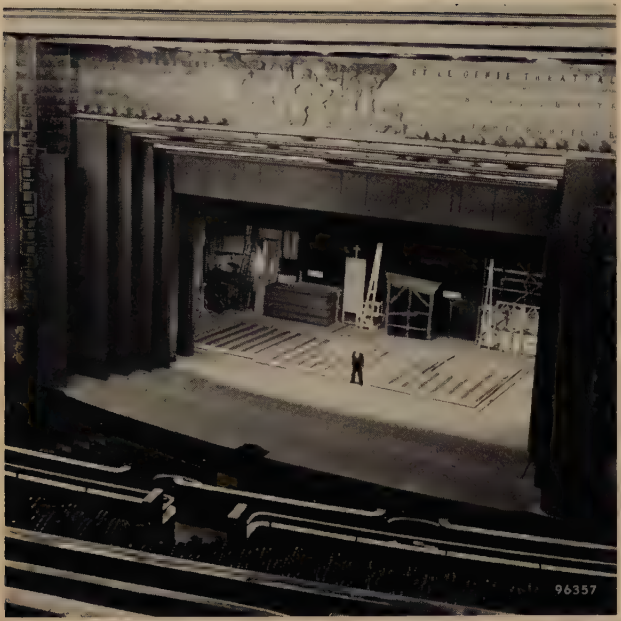


Fig. 11. The stage in the Palais de Chaillot, Paris. Loudspeaker columns for reinforcing the direct sound can be seen on the left and right of the stage (see also fig. 12). Loudspeakers for indirect (diffuse) sound are mounted above the stage.

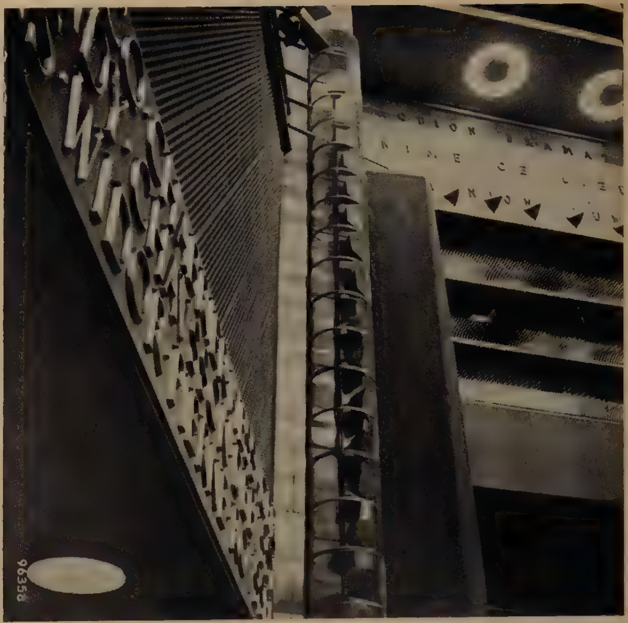


Fig. 12. One of the loudspeaker columns shown in fig. 11. The constituent loudspeakers point in different directions in order to radiate the high tones uniformly throughout the auditorium.

Beamed loudspeakers are used not only in enclosures but also in the open air. A striking example is shown in *fig. 13*. In an open-air sound reinforcement system beamed loudspeakers serve a dual function. In the first place the radiated sound is concentrated in the direction of the listeners, which makes it possible to limit the power of the amplifiers and loudspeakers required. In the second place less nuisance is caused in the surroundings, and the reproduction is not spoiled by reflections from nearby buildings. Besides columns of cone-type loudspeakers, which radiate mainly in a flat lobe, use is also made of individual horn-type loudspeakers, which radiate the sound within a conical region about the axis. The radiating angle of the cone is practically the same as that of a loudspeaker column whose length is equal to the diameter of the mouth of the horn. Horn loudspeakers combine a high efficiency with excellent weather-resistant properties. For the reproduction of music, however, their drawback is that the horn cuts off low notes below a certain frequency which is determined by the flare of the horn. If the cut-off frequency is not to be too high the cross-sectional area of the horn should increase very gradually, but in that case it would become impracticably long. For this reason considerable use is made of folded horns (*fig. 14*). For outdoor purposes, especially where sound of considerable intensity is required to cover a large area, as on airfield runways and in dock installations, columns of horn loudspeakers are often

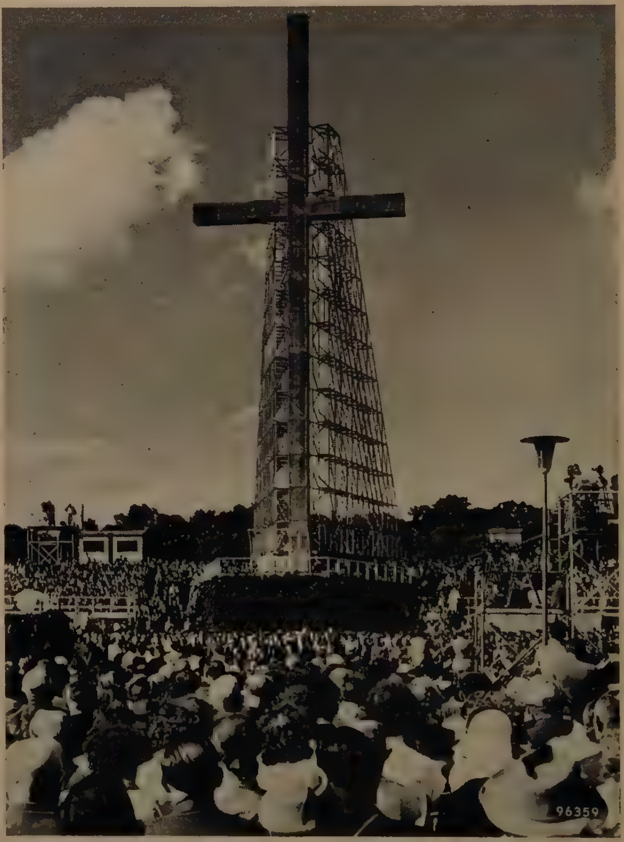


Fig. 13. Evangelical Church Congress, held on the Rebstock airfield near Frankfurt am Main (1956). In the vertical beam of the 40-metre high Cross, loudspeakers were mounted to form a sound column 30 metres long. The speaker on the platform could be clearly understood all over the ground, covering some 50 acres and on which a crowd of over 300 000 was assembled. At the end of the congress the installation was used for controlling the traffic.

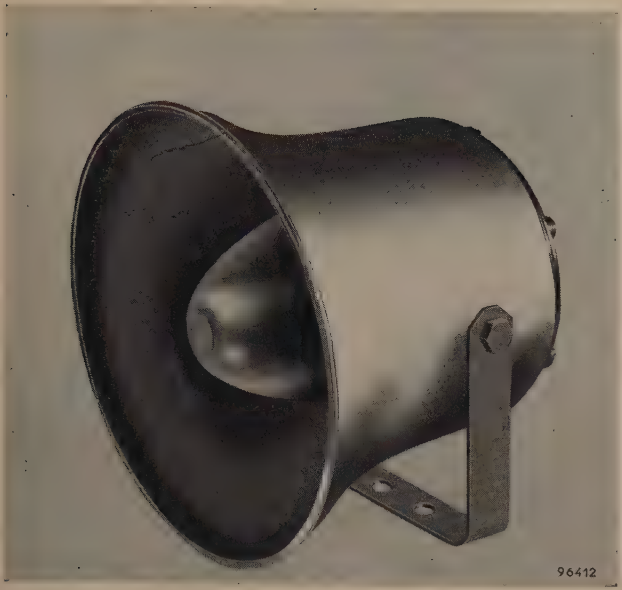


Fig. 14. Folded-horn loudspeaker.

employed which combine the advantages of the horn with additional beaming in the vertical plane.

A special form of horn loudspeaker is the multi-cellular type (*fig. 15*), which is used in cinemas for high-note distribution. The beams from the individual cells uniformly fill a wide solid angle, thus providing even distribution of the high notes.

In some cases, a central loudspeaker group for beaming direct sound is inadequate. Some examples are the following.

1) In the open air, *a*) when the contour of the ground is awkward, *b*) when it is windy, and the sound is, as it were, blown away, and *c*) when a temperature gradient exists; this phenomenon may bend the beam so far up or down that it no longer reaches the listeners (*fig. 16*).

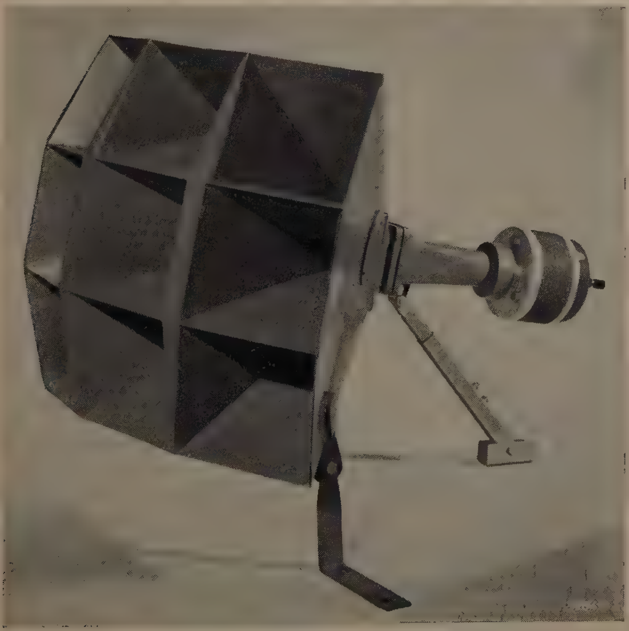


Fig. 15. Multi-cellular horn, much used in cinemas for uniformly radiating the high notes.

2) In those theatres where the sound from the loudspeaker columns beside the stage does not adequately penetrate to the boxes or to the low space under the balcony.
3) In enclosures such as large churches and factory workshops where there are relatively few listeners, so that even with a highly directional loudspeaker group too much sound still strikes reflecting surfaces, thus producing excessive reverberation.

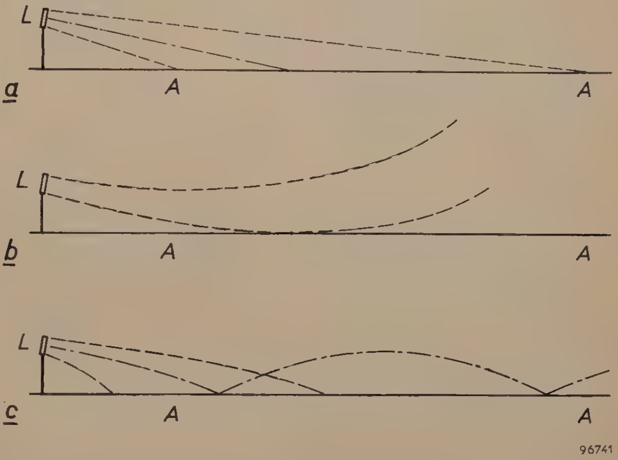


Fig. 16. Effect of a temperature gradient on the direction of sound. *a*) No temperature gradient. The sound from the loudspeaker column L is directed on to the audience A-A. *b*) The temperature drops with increasing height. Since the velocity of sound in warm air is greater than in cold air, the beam is refracted upwards and reaches only part of the audience. *c*) The temperature rises with increasing height. The beam is refracted downwards and only reaches the audience at the front. If the ground reflects strongly, the beam is again deflected upwards and bent downwards further on; in such conditions the sound has an exceptionally long range.

The solution in such cases is to install, instead of one central loudspeaker group, a larger number of loudspeakers with smaller fields of coverage, distributed according to the circumstances. The loudspeakers not required for certain occasions should preferably be switched off so as not to cause more reverberation than is unavoidable.

Where the fields of coverage of the loudspeakers coincide they may interfere with each other at places where they are not only almost equally loud but moreover arrive with a time difference of more than 50 milliseconds. There is a particular danger of this happening when dispersed loudspeaker columns are in use. The difficulty can be overcome by connecting the loudspeakers via a time-delay system (see below) which delays the signal to each loudspeaker to an extent corresponding to the air propagation time from the source to that loudspeaker (*fig. 17*). *Fig. 18* shows a large open-air installation in which this principle was applied. The same method is also used in the "Volkswagen" factory public address system, to be described in part II of this article.

It is sometimes advantageous to make the delays 10 to 20 milliseconds longer than corresponds to the position of the loudspeakers. In this case the impression of direction is determined, as we have seen, by the sound first to arrive — even when it is up to about 10 dB weaker than the sound from the nearest loudspeaker. In this way the natural stereophonic effect of speech (whether directly from the stage or from the stereophonic loudspeaker columns beside the stage) is preserved for the audience at the rear, who hear the sound principally via the delayed loudspeakers.

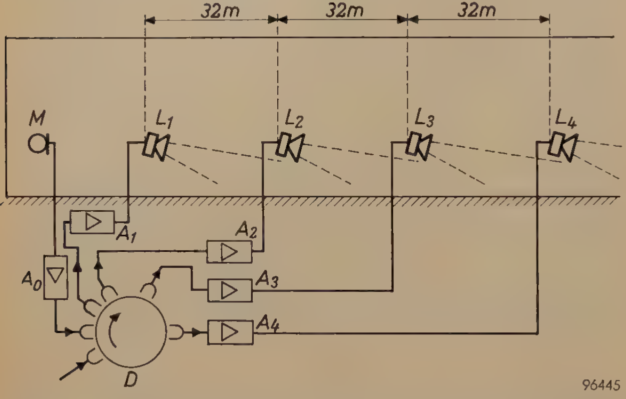


Fig. 17. Decentralized arrangement of loudspeakers for making speech intelligible in a long factory workshop with hard walls. *M* microphone. L_1, L_2, L_3 and L_4 are loudspeaker columns each of which cover e.g. a distance of 32 metres, corresponding to a sound transit time of 100 milliseconds. To prevent the loudspeakers interfering with each other, the electrical signal for L_2 is delayed 100 milliseconds with respect to that for L_1, the signal for L_3 100 milliseconds with respect to L_2 and so on. *D* is the delay system. $A_0 \dots A_4$ are amplifiers.

Indirect sound

If an auditorium whose reverberation time is too short is to be made suitable for music, it is necessary to augment the indirect sound. The problem here is that the natural indirect sound is composed of an enormous number of reflections from all parts of the walls, whereas with sound produced electro-acoustically one is naturally limited to a finite number of loudspeakers.

The solution of this problem by means of *ambiophony* [11]) has already been described in this

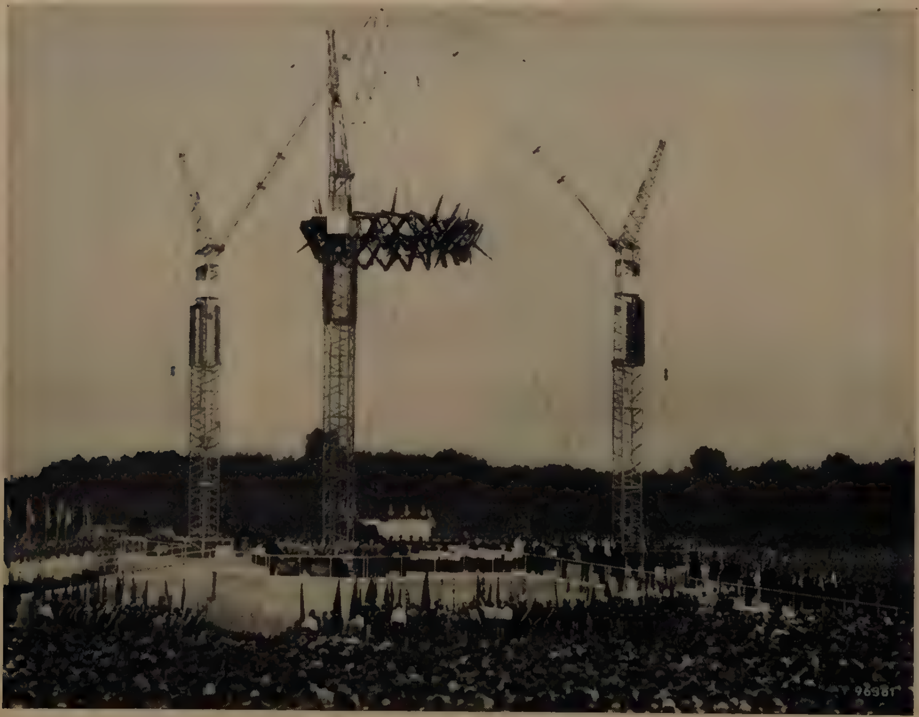


Fig. 18. Catholic Church Congress held in Cologne (1956) and attended by some 800 000 persons. Loudspeakers mounted in the symbol of the Crown of Thorns radiated sound to the distant parts of the ground. The regions nearer to the platform were covered by nine loudspeaker columns, mounted in the steel masts. To compensate for the difference in arrival time between the sound from the loudspeakers in the symbolic Crown and the sound from the columns, the signal through the columns was delayed such that both sounds reached the audience at the same time.

---

[11]) A new term introduced to replace the formerly used "stereo-reverberation". It appears that the latter is sometimes confused with stereophony — often abbreviated to stereo. The risk of confusion is all the greater since the advent of the stereophonic gramophone record which is making stereophony — or stereo — familiar to the general public. It is hoped that the introduction of the term *ambiophony* will put an end to this confusion.

review [3]) and elsewhere [12]). It will therefore suffice here to briefly recapitulate the essentials of an ambiophonic installation. Above the orchestra a microphone *M* is suspended (*fig. 19*), the signal from which is recorded by a magnetic recording head *0* situated at the periphery of a rotating wheel *W*, the delay wheel. The recording successively passes four playback heads *1 . . . 4* and an erasing head *5*; the latter ensures that the magnetic layer *m* is blank on returning to the recording head. The signals induced in the playback heads are delayed with respect to the microphone signal by varying degrees, depending on the speed of the wheel and on the distance, measured on the periphery, between the recording head and the playback head in question. Each of the playback heads is connected via its own amplifier to a group of loudspeakers appropriately disposed around the auditorium. The function of the loudspeakers is to radiate *diffuse* sound. To this end they are arranged around the auditorium in such a way that as little as possible of their energy is directly radiated on to the audience. The required effect can be achieved by giving each of these groups the correct intensity and timbre and the appropriate delay, and by applying electrical feedback from the playback heads to the recording head. The diffuse and delayed sound thus produced supplements the inadequate indirect sound from the walls of the auditorium. The sound can be produced for the most part by loudspeakers without the listeners being aware of it. The adjustment of the equipment is fairly critical; exaggeration detracts from the naturalness and betrays the presence of the installation. Experience has shown that, provided the system is properly operated, ambiophony appreciably improves the quality of a performance, and that actors and musicians of repute welcome its help.

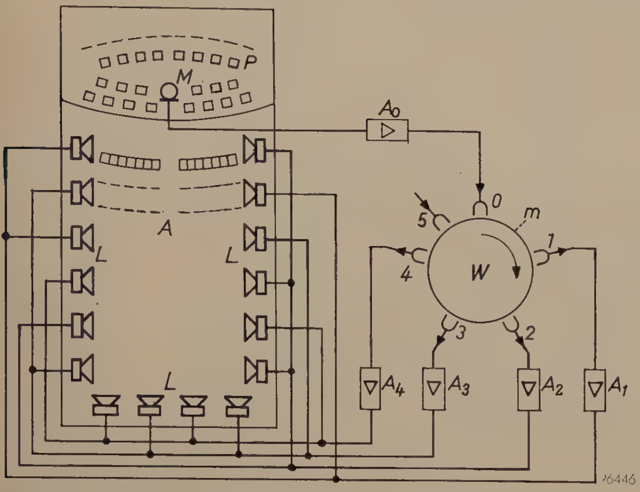


Fig. 19. Installation for ambiophony. *A* auditorium. *P* platform. *M* microphone. *W* delay wheel, coated on the edge with magnetic material *m* for magnetic recording. *0* recording head. *1 . . . 4* playback heads. *5* erasing head. $A_0 \ldots A_4$ amplifiers. *L* loudspeakers. Electrical feedback (not shown) can be applied from playback heads to the recording head.

An ambiophonic installation can also serve to suggest to the listeners that they are seated in a hall of greater size. The caption to *fig. 20* explains the method of calculating the delays to be applied to the various loudspeakers for this purpose.

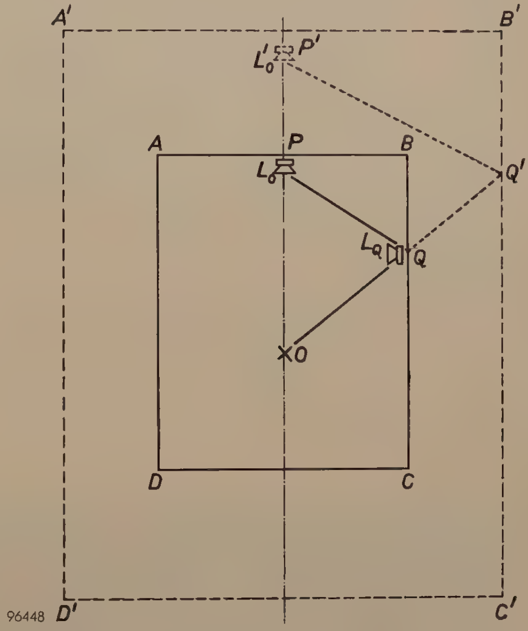


Fig. 20. Method of calculating by how much an arbitrary loudspeaker L_Q at a given position on the auditorium wall *ABCD* should be delayed in an ambiophonic installation in order 1) for an observer *O* to receive an impression of the true size of the hall, and 2) to receive the impression of being in a large enclosure (*A'B'C'D'*).

1) The loudspeaker L_Q must simulate a reflection at *Q* of sound emanating from the source L_0 at *P*. The signal for L_Q must be delayed by a time corresponding to the path *PQ*, i.e. by

$$\Delta t = \frac{PQ}{c},$$

where *c* is the velocity of sound.

2) To create the illusion of a larger auditorium, L_Q must give the impression that sound originating from an imaginary source L_0' at *P'* is reflected from the imaginary wall *B'C'* at point *Q'*. The delay required for L_Q is now determined by the path length $P'Q' + Q'Q$, less the length PP' (the actual source still being at *P*). Hence:

$$\Delta t = \frac{P'Q' + Q'Q - PP'}{c}.$$

By repeating the construction for various points *Q*, delays can be found that should be applied to the loudspeakers L_Q around the auditorium in order to suggest the primary reflections in the simulated larger auditorium. Furthermore, to simulate the multiple reflections, other loudspeakers are needed between these loudspeakers and with greater delays.

The results of the construction depend little on the position of the point *O*.

---

[12]) See contribution by R. Vermeulen in the book Musik, Raumgestaltung, Elektroakustik, edited by W. Meyer-Eppler, Arsviva Verlag (H. Scherchen), Mainz 1955; see also D. Kleis, Experimente zur Verbesserung der Raumwirkung von Schall, Elektron. Rdsch. **9**, 64-68, 1955.

The lack of good musical acoustics is particularly felt in an open-air concert. The absence of wall reflections reduces the loudness and the music lacks "body", so that an outdoor performance by a first-class orchestra is often a disappointment to the listeners. These drawbacks can be overcome by supporting the performance electro-acoustically (see *fig. 21*). The direct sound can be brought to the required level by amplifying the orchestral music stereophonically and relaying through loudspeaker columns beside or above the orchestral platform. Moreover, by the addition of diffuse and delayed sound the music can be given more body, without diminishing in any way the pleasant atmosphere peculiar to a concert in the open air. The aim in such cases should be solely to enrich the sound of the music and not to emulate the acoustics of a concert hall. Since reverberation is essentially incompatible with an open-air performance, no feedback in the delay installation is normally applied in this case.

A delay wheel is also employed for compensating differences in the transit time of direct sound, as discussed above (figs. 17 and 18).

A delay wheel in its present-day form is shown in *fig. 22*; some particulars are described in the caption. *Fig. 23* shows a photograph of the complete ambiophonic installation, type EL 6910.

An auditorium provided with both installations — one for reinforcing the direct sound and one for adding ambiophony — is entirely independent of its original acoustics. *The sound installations are capable within wide limits of giving the auditorium any acoustic properties that may be required.* By appropriately selecting the delay times of the indirect sound and the ratio of direct to indirect sound it is possible to adapt to the circumstances both the apparent size of the hall and the apparent distance of the sound source from the listeners, i.e. the "relief" or auditory perspective of the auditorium. Thus the conditions most favourable for stage plays as well as for music can be created in one and the same hall. Moreover, by controlling the timbre of the indirect sound, it is possible to suggest different wall textures (stone, wood, etc.).

Microphones

Like the arrangement of loudspeakers, the positioning of the microphones constitutes a problem of acoustic adaptation that cannot be regarded separately from the auditorium. Where the microphones are used for making magnetic tape recordings, intended to be played back during the performance, or where they are situated in a separate room from which the music is to be relayed to the

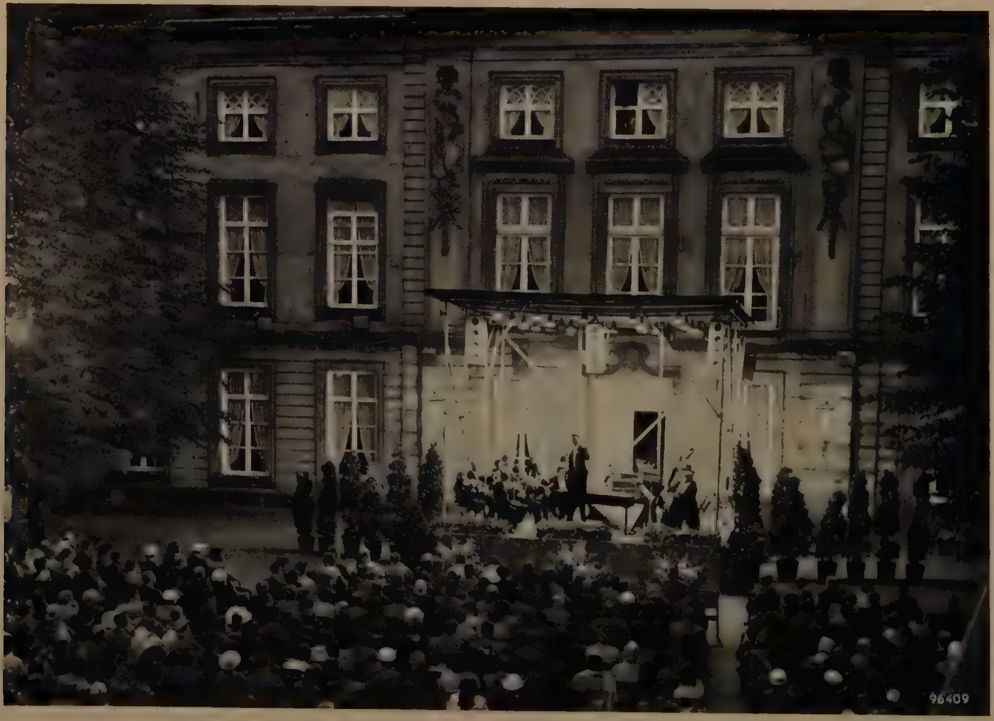


Fig. 21. Open-air concert given by the Brabant Chamber Orchestra, conducted by Evert van Tright, on the square in front of the County Hall in 's-Hertogenbosch (June and July 1958). Above the platform, loudpeaker columns are mounted for stereophonically reinforcing the direct sound. Other loudspeakers are mounted on the façade of the building and in the trees for adding diffuse and delayed sound. With this arrangement the music was given a noticeably richer tone without simulating the acoustics of a concert hall and without detracting from the pleasant atmosphere of an open-air concert.

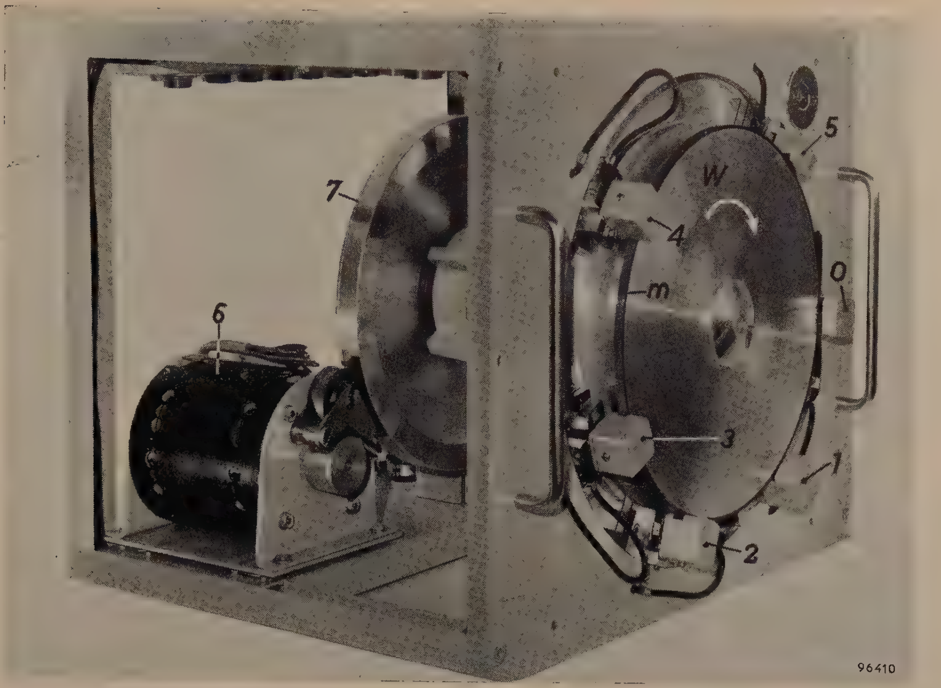


Fig. 22. Delay wheel *W* with magnetically coated rim *m*, recording head *0*, playback heads *1*, *2*, *3* and *4*, erasing head *5*, drive motor *6* and flywheel *7*. This unit is a component of the ambiophonic installation EL 6910 (see fig. 23).

The maximum delay for the fourth playback head is either 0.25 or 0.5 seconds, depending on whether the peripheral speed of the wheel is 3 or 1.5 m/sec. These two speeds are obtained by changing the number of effective poles of the drive motor. Between the magnetic layer and the various heads there is an air gap of approximately 20 microns, so that there is no mechanical contact between the layer and the heads, giving the wheel an almost unlimited useful life. The eccentricity of the wheel is less than 1 micron, the non-uniformity in the speed less than 0.01%.

auditorium, they can be arranged in accordance with conventional studio technique. Care should be taken to ensure that the microphones pick up primarily direct sound and as little as possible of reverberant sound and noise. The latter are much more perceptible when reproduced by a loudspeaker than when they are heard directly, for in the former case they cannot be dissociated by binaural location from the recorded direct sound. (For this reason broadcasting studios are always damped more than auditoria used for public performances.)

The microphones situated in the auditorium pick up in principle not only the sound from the stage or the platform but also the sound from the loudspeakers, the noise of the audience and the reverberation of the auditorium. If the microphones pick up the sound from loudspeakers to which they are themselves connected, the result is acoustic feedback. This is most pronounced for those frequencies of the sound spectrum that arrive at the microphone in a certain phase. The consequence is that notes of these frequencies receive additional amplification and hence a longer reverberation time. This preference for certain frequencies and the persistence of the associated notes are particularly troublesome effects which immediately betray the electro-acous-

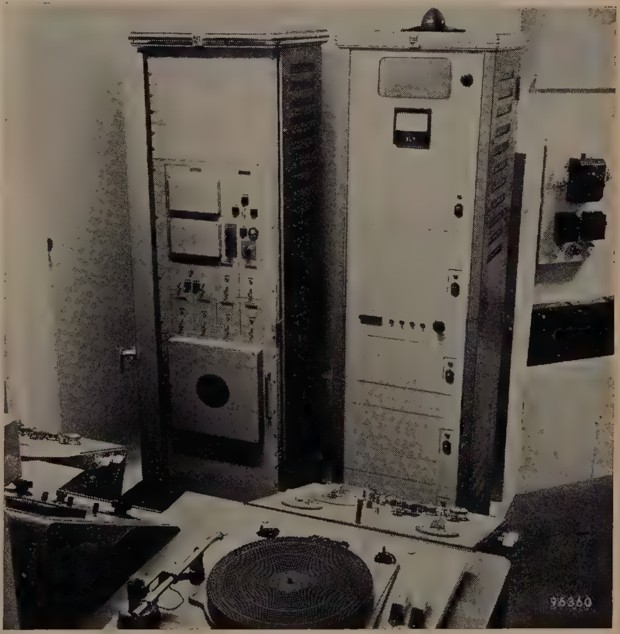


Fig. 23. Ambiophonic installation EL 6910 (left background) in the acoustic control room in the Palais de Chaillot. The reverberation time, and in each channel the loudness and timbre of the sound, can be adjusted either on the apparatus itself or remotely from a central mixing and control desk. The amplifiers are fitted with "Special Quality" tubes and have a frequency characteristic which is flat to within 1 dB from 160 to 12 000 c/s for 3 m/sec peripheral speed of the delay wheel and from 80 to 8000 c/s for 1.5 m/sec.

tical nature of the sound and adversely affect its quality. These effects are all the more troublesome the higher the amplification, which makes certain notes progressively more pronounced and more persistent. If the amplification exceeds a certain limit, the most pronounced preferred tone will not decay at all, and the installation will "howl". The occurrence of this in practice is obviously due to a gross error of operation. The undue persistence of certain notes is one of the most frequent complaints made about sound installations. In a well-designed system it is an unmistakable sign that the volume is turned up too high, another result of which, as already mentioned, is the exaggerated reproduction of the low notes.

The problem of avoiding acoustic feedback in theatre installations is made more difficult by the necessity to install the microphones unobtrusively or even out of sight. This means that the distance from the microphones to the artist on the stage or to the orchestra must always be fairly considerable. The only solution is to use microphones with marked directional characteristics.

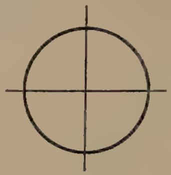
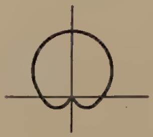
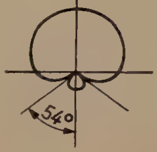
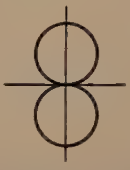
The usefulness of a microphone in this respect is expressed by the ratio of its response in the preferred direction to the integrated omni-directional response, the front-to-random ratio. This ratio, then, is 0 dB for omni-directional microphones; for cardioid and ribbon microphones it is 5 dB, and for hypercardioid types 6 dB (see *table*).

To obtain a still better ratio, microphones can be grouped together to form a so-called "line" microphone [13]). The directivity pattern of a line microphone is identical to that of the radiation pattern of a loudspeaker column. The preferred directions lie mainly within a flat disc-shaped lobe lying symmetrically about the median plane of the line and subtending an angle which decreases with increasing length of the line and with increasing sound frequency.

Another solution is to use a "higher-order gradient microphone", which consists of two microphones mounted closely together with their diaphragms parallel, and connected in anti-phase. This leads to a more pronounced directional effect, although at the expense of the low-tone response. As we have seen, however, the latter may often be an advantage rather than a drawback.

The use of microphones sharply directed on to the stage not only reduces acoustic feedback but also the noise and reverberation picked up from the auditorium.

The best place to set up the microphones is often the front edge of the stage. Since the microphones cannot be approached closer than about 5 feet, the artists have considerable freedom of movement, without this giving rise to any noticeable intensity differences in the sound from the loudspeakers. This does much to help create a natural impression.

Type of microphone	Polar diagram	Front-to-random ratio
Omnidirectional		0 dB
Cardioid		5 dB
Hypercardioid		6 dB
Ribbon		5 dB

The microphone arrangement which, having regard to the above considerations, is best suited to give uniform pick-up (whether stereophonic or not) of the sound from stage, platform or orchestral pit, must of course be decided according to the given conditions. In part II of this article we shall discuss at greater length the arrangements in a number of sound installations.

Summary. Modern acoustical engineering is based on the properties of hearing and the acoustic properties of auditoriums. Both these subjects are briefly discussed. Many auditoriums are acoustically unsuited to the purpose for which they are to be used. Frequently, too, conflicting demands are made on the acoustics of an auditorium, for example when a hall is required to serve both for theatrical performances and for concerts. In such cases the solution is to install two electro-acoustical systems which together make it possible to exercise complete control over the auditorium acoustics. The one system serves for stereophonically reinforcing the direct sound, which is directed towards the audience by directional loudspeakers. The other system serves for introducing indirect, diffuse sound (ambiophony). By controlling the reverberation time of the indirect sound, an impression of spaciousness can be suggested. Theatrical performances can be additionally supported by means of "panoramic sound" (e.g. effect sounds from around or above the auditorium). Sound systems for large open-air meetings and outdoor concerts are also discussed. The author concludes with some comments on the arrangement of microphones.

---

[13]) Philips tech. Rev. 17, 262, 1955/56, figs. 5 and 6.

COLOUR TELEVISION IN MEDICAL TEACHING

621.397.3:378.4:61

How to demonstrate surgical operations in such a way that they can be followed closely by large numbers of students is a problem of some antiquity in medical teaching. A significant step was taken towards its solution when advances in television engineering made it possible to project bright pictures of considerable dimensions. When the Philips projection system [1]) was introduced, its utility for medical teaching was quickly recognized. The system was demonstrated in the University Hospital at Leyden in February 1949, when an operation was followed on the television projection screen by more than 200 spectators [2]).

With the advent of colour television it has become possible to add colour information to the projected picture. The fact that this helps the spectators to understand what they see is illustrated in *fig. 1*, which shows the same surgical object in black-and-white and in colour.

Another important development in the last ten years has been the improvement of the variable-focus lens, or "zoom" lens. With this instrument the size of the field of view can be continuously varied, so that both general views and close-ups can be televised without shifting the camera.

These considerations induced the University of Marseilles to acquire for its Faculty of Medicine a closed-circuit colour-television system capable of projecting a very large picture (2.70 × 3.60 m). The installation, which was put into operation in October 1958, is briefly described below.

A diagram of the layout is given in *fig. 2*. In the operating theatre A the television camera is attached to the lamp above the operating table (see also *fig. 3*). The camera "sees" the brightly lit object (luminous intensity 20 000 to 30 000 lux) reflected in a flat mirror, which is mounted obliquely on the lamp and so coupled to it that if the lamp is turned the camera continues to see the illuminated field (fig. 2).

The camera contains three photoconductive

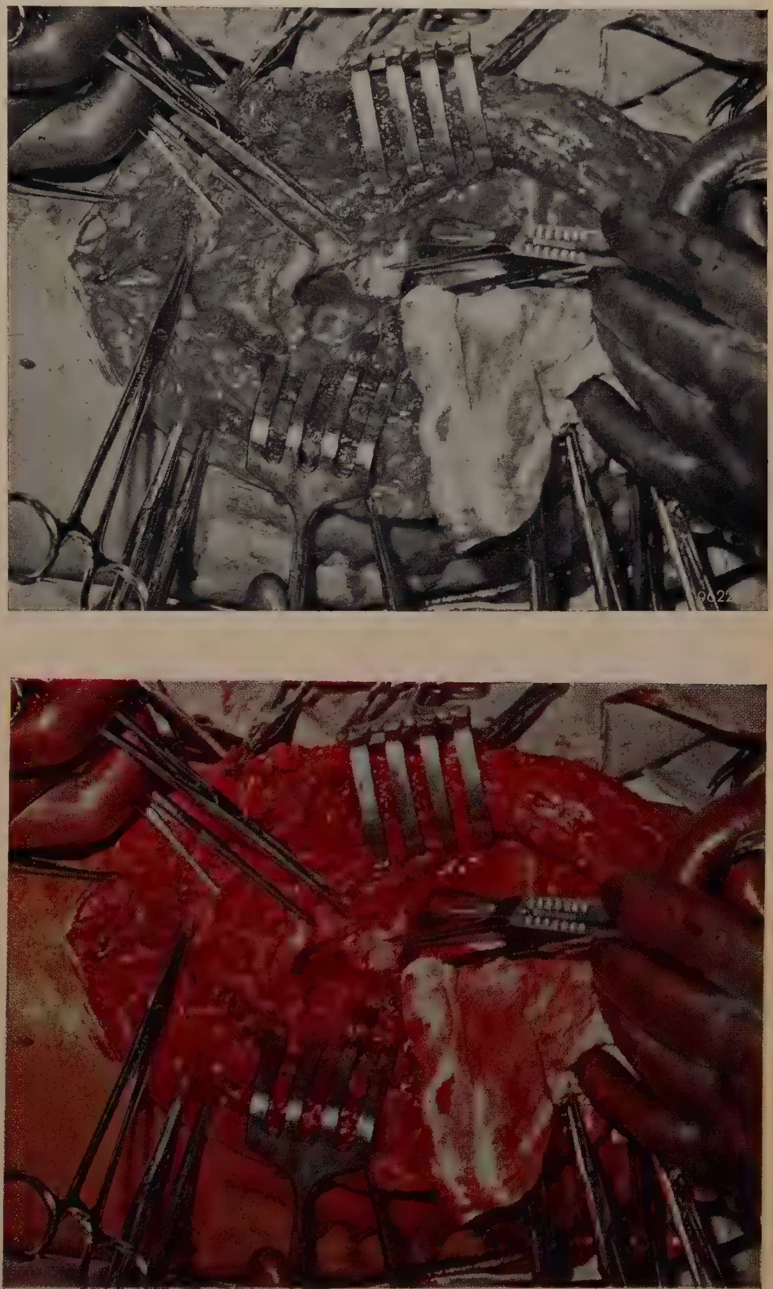
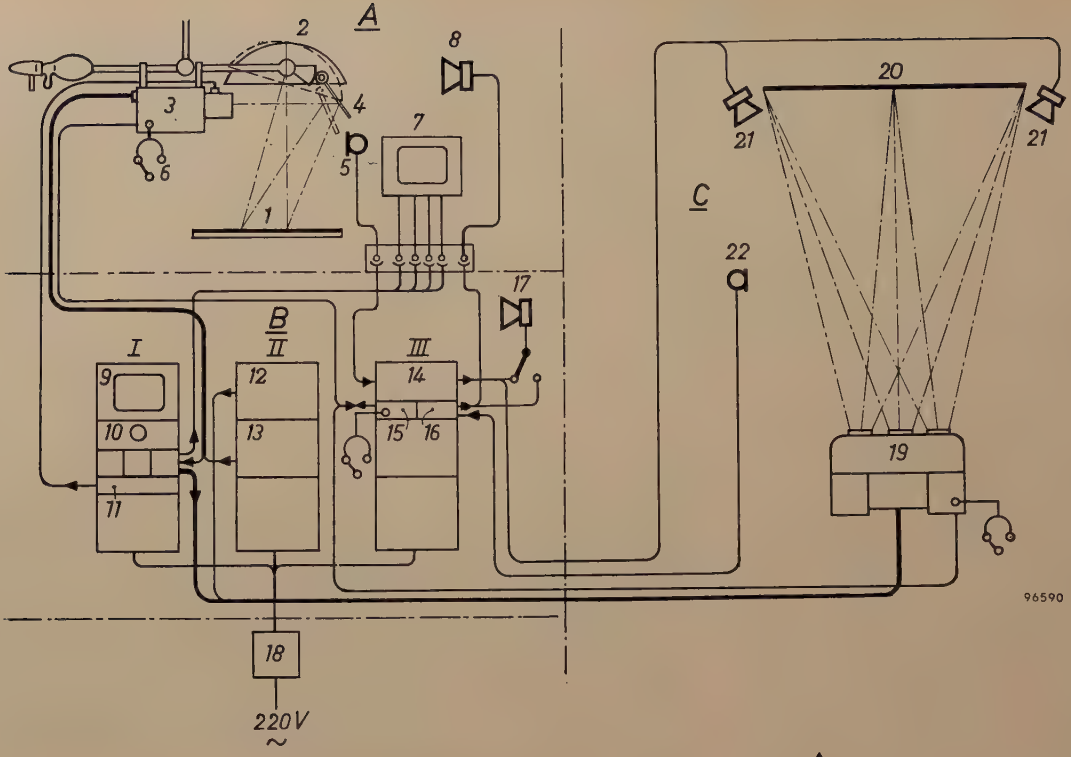


Fig. 1. A coloured picture of a surgical object shows details far more clearly than a monochrome one.

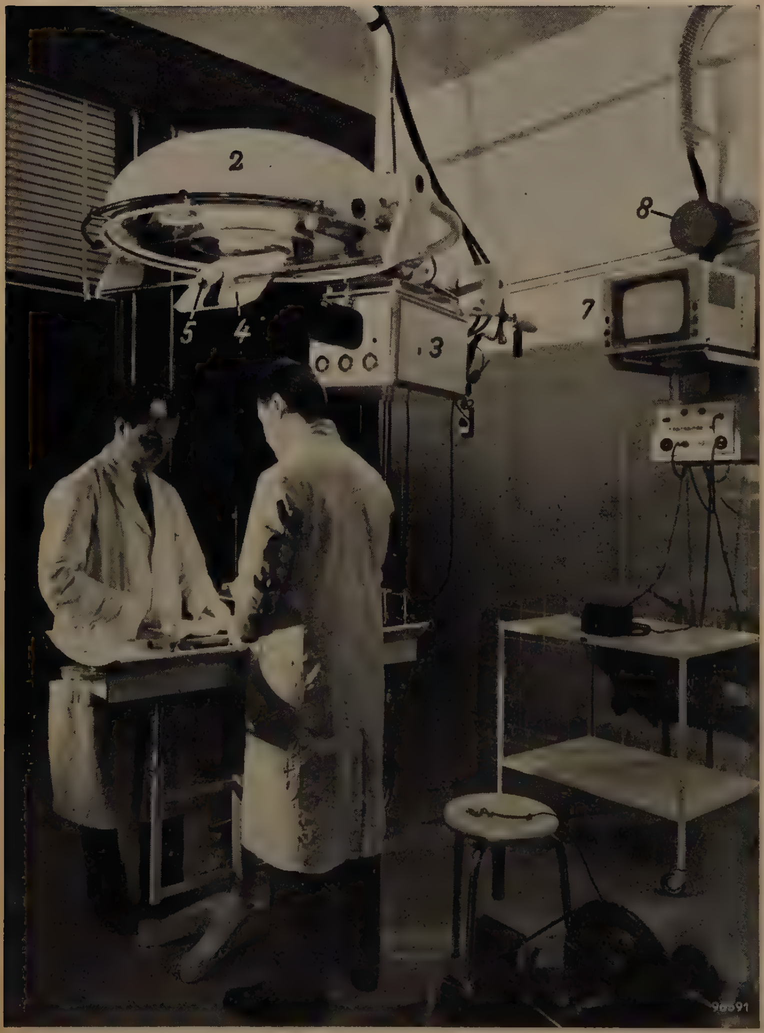
---

[1]) H. Rinia, J. de Gier and P. M. van Alphen, Home projection television, I. Cathode-ray tube and optical system, Proc. Inst. Rad. Engrs. **36**, 395-400, 1948.
P. M. van Alphen and H. Rinia, Projection-television receiver, I. The optical system for the projection, Philips tech. Rev. **10**, 69-78, 1948/49.

[2]) Philips tech. Rev. **11**, 42, 1949/50.



↑ Fig. 2



← Fig. 3

Fig. 2. Layout of the closed-circuit colour television system installed in the Department of Medicine at the University of Marseilles (the following photographs all relate to this installation).

A. Operating theatre containing operating table *1*, lamp *2*, colour-television camera *3*, mirror *4*, microphone *5*, headphone with microphone *6*, monochrome monitor *7*, loudspeaker *8*.

B. Control room containing racks *I*, *II* *III*. Rack *I* includes a monitor *9*, an oscilloscope *10* and a panel *11* containing the controls for adjusting the camera lens system (focus, focal length, aperture: these can also be controlled from the operating theatre). In Rack *II*, *12* delivers a test signal and *13* the scanning currents and correction signals for the camera. Rack *III* contains a 70 W amplifier *14* and two 2 W amplifiers *15* and *16*. Loudspeaker *17* enables the control-room operator to listen-in on both sound channels. *18* is the voltage stabilizer (5 kVA).

C. Lecture theatre with colour-television projector *19*, projection screen *20*, loudspeaker columns *21* and microphone *22*.

Fig. 3. The operating theatre. The lamp *2* (numbering as in fig. 2) and the colour camera *3* are mounted on a bracket. The lamp carries the tilted mirror *4*, to the back of which a microphone *5* is fixed. Right, the picture monitor *7* and loudspeaker *8*. None of the equipment obstructs the surgeons.

camera tubes [3]). Dichroic mirrors and filters transmit the red, green and blue components of the incident light to their respective camera tubes [4]). The lens system ("Pan Cinor", made by S.O.M. Berthiot) has a continuously variable focal length of 42 to 170 mm, corresponding to a field of view of 30 to 7.5 cm diameter on the operating table. Focussing, zooming (changing the focal length) and adjustment of the diaphragm of the lens is done by remote control either from the operating theatre or from the control room. A feature of the lens system is that there is enough space between the last lens and the camera tubes for the dichroic mirrors and filters.

The operating theatre further contains a monochrome picture monitor (this could also be a colour picture monitor), on which the three primary-colour pictures can be checked separately or in combination.

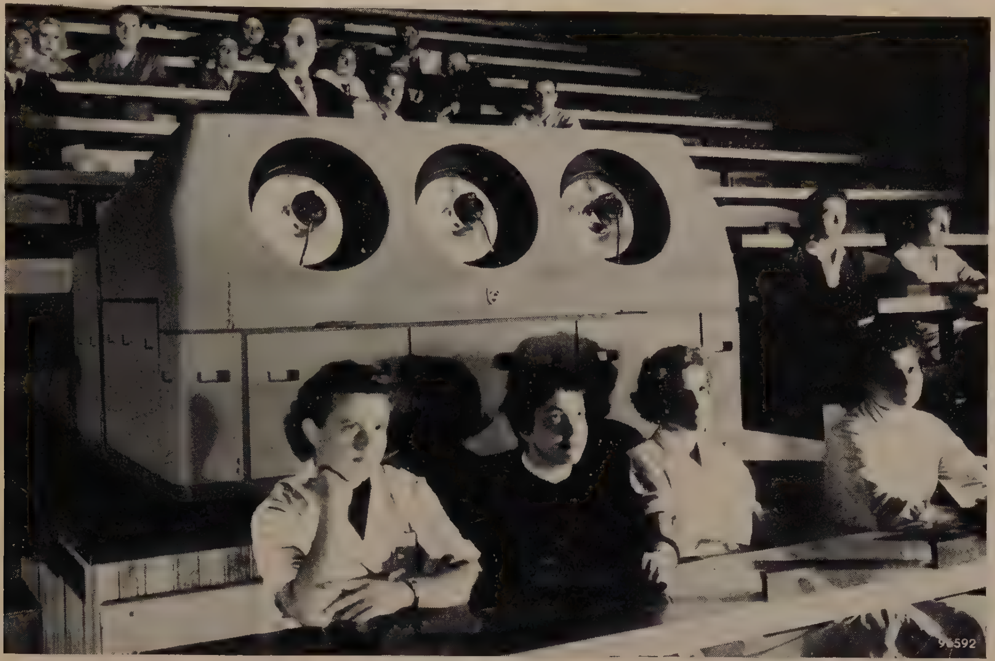


Fig. 4. The colour-television projector in the lecture theatre. The primary-colour projectors (red, green, blue) are mounted side by side [5]).

As fig. 3 shows, none of the parts of the installation obstruct the surgeons.

The three primary-colour signals are transmitted by cable via the control room — which we shall discuss presently — to the lecture theatre (*C* in fig. 2). The projection system installed here (*figs. 4* and *5*) is of a type already dealt with at length in this Review [5]). It consists of three primary-colour projectors side by side, each incorporating a Schmidt optical system and a projection tube giving red, green and blue light, respectively. As described in

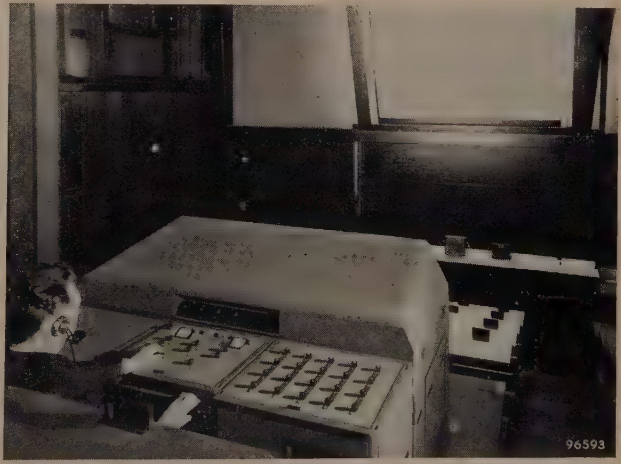


Fig. 5. The control desk for the colour-television projector. The picture on the screen measures 2.70 × 3.60 m and has a highlight luminance of 14 cd/m^2.

---

[3] P. K. Weimer, S. V. Forgue and R. R. Goodrich, The Vidicon photoconductive camera tube, R. C. A. Rev. **12**, 306-313, 1951. L. Heijne, P. Schagen and H. Bruining, An experimental photoconductive camera tube for television, Philips tech. Rev. **16**, 23-25, 1954/55.

[4] P. M. van Alphen, Applications of the interference of light in thin films, Philips tech. Rev. **19**, 59-67, 1957/58 (No. 2); see especially p. 65 et seq.

[5] T. Poorter and F. W. de Vrijer, The projection of colour-television pictures, Philips tech. Rev. **19**, 338-355, 1957/58 (No. 12); see especially figs. 20, 21 and 22.

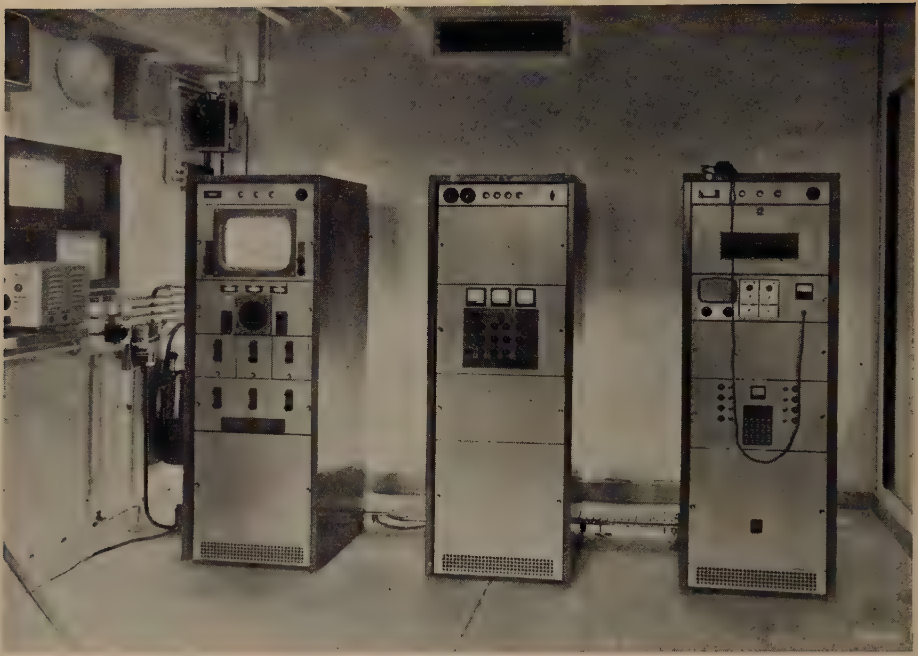


Fig. 6. The three racks in the control room (cf. fig. 2). The wall on the left is the rear wall of the lecture theatre. The operator can see the projected picture through the window.

article [5]), the three primary-colour images are brought into superposition on the projection screen partly by mechanical means (the outside projectors are pointed slightly inwards) and partly by electrical means (correction signals are added to the scanning currents). Effective measures are taken to provide protection against the X-rays generated in the projection tubes, which operate at 50 kV.

The picture on the screen (fig. 5) — beaded screen with a gain factor of about 2.5 — measures 2.70 × 3.60 m and has a highlight luminance of 14 cd/m^2. When the smallest field of view is used the projected image of a 7.5 cm object fills the whole screen height; this represents a linear magnification of about 36×. The size, definition, brightness and contrast of the projected picture are such that each spectator in the 300-seat lecture theatre can follow every detail of the operation. The result would still be amply satisfactory in a lecture theatre seating 500.

The control room (*B* in fig. 2) is equipped with three racks as shown in *fig. 6*. Rack *I* contains a picture monitor similar to that in the operating theatre, and an oscilloscope for checking the amplitude and waveform of the three primary-colour signals.

Rack *II* supplies the scanning currents and correction signals for the camera tubes (the picture is scanned on the 625 line system). This rack also contains the circuits generating the synchronizing signals for the camera and the colour projector, and a test signal for checking the colour projector distinct from the camera.

Rack *III* contains the amplifiers for the sound installation, viz. one 70 W amplifier and two 2W amplifiers. The first operates two loudspeaker columns, which are mounted at either side of the projection screen, and over which the commentary from the operating room is given. A limiter circuit in the amplifier prevents distortion if the speaker should approach too close to the microphone (which is attached to the back of the mirror); this allows the speaker appreciable freedom of movement in relation to the microphone. One of the 2W amplifiers serves the intercommunication system of headphones and microphones between the operating theatre, the control room and the projectionist. The other 2W amplifier connects a microphone in the lecture theatre to a loudspeaker in the operating theatre. A loudspeaker in the control room enables the operator stationed there to listen-in on this channel as well as on the 70W-amplifier channel.

The whole installation is powered from the mains via a 5 kVA voltage stablizer.

It is evident that the usefulness of this installation is not confined to instruction in surgery. Dentistry, anatomy, autopsies, sterilization technique, etc., can similarly be demonstrated to large audiences, not only for the teaching of medical students but also for the training courses provided in hospitals for the nursing staff.

W. A. HOLM and F. H. J. van der POEL.

AN APPARATUS FOR CINEFLUOROGRAPHY WITH AN 11-INCH X-RAY IMAGE INTENSIFIER

by J. J. C. HARDENBERG.

621.386.17:621.386.832.032.217.2:
616-073.75

The radiograph (or X-ray photograph) owes its importance in medical diagnostic practice to the wealth of anatomical information it provides on the state or location of tissues and organs in the human body and on their pathological disorders. Cinefluorography (or X-ray cinematography), which has become practicable since the advent of the image intensifier, goes a step further inasmuch as it records the normal or abnormal behaviour of the organs while they are performing their function. Films made in this way yield valuable physiological information for diagnostic and instructional purposes.

The apparatus described below, with its large image field, makes it possible to examine cinematographically the large organs, such as the heart, the stomach and the lungs.

Members of various departments of the Philips factories have contributed to the development of this equipment, in particular J. R. Boerman, J. H. J. Maartens and J. H. A. Moubis of the Electron Tubes Division, and P. J. M. Botden, J. Fransen and A. Verboon of the X-ray and Medical Apparatus Division.

In medical X-ray examinations the technique of serial (spot-film) radiography occupies an important place. The movements of the organs to be examined, e.g. the gastro-intestinal organs, made visible by a contrast medium administered to the patient, are observed on the fluoroscopic screen and a radiograph is taken at the instant a diagnostically significant phase is seen to appear.

Where the movements of the object are rapid (as, for example, the deglutition of the oesophagus, the pulsation of blood-vessel walls, the peristalsis of the duodenum) it is necessary to take a number of spot-film radiographs in quick succession. Keeping to the method of direct radiography this has been effected by means of a mechanical device which changes the film approximately 10 times per second. A more elegant solution is that offered by fluorography, whereby photographs of reduced size are taken of the fluoroscopic image, the sequence of photographs being recorded on a rapidly transported roll of film of e.g. 70 mm width [1]). A series of such photographs offers for a diagnosis not only the anatomical information given by a single radiograph but also physiological information, inasmuch as the movement of an organ can be reconstructed by measuring geometrical changes (in particular the displacement of the contrast medium) in the successive photographs.

It would seem but a small step from this to X-ray cinematography or cinefluorography, i.e. to provide a permanent film record which, when cinematographically projected, gives a direct representation of the movement of the examined object. Compared with the original observation of the moving image on the fluoroscopic screen a cinefluorographic record has important advantages: the doctor is able to study a phenomenon at leisure over and over again, at a favourable luminance level and, if desired, together with colleagues or students; the film constitutes a documentary support for a diagnosis based on physiological abnormalities; and it is possible to follow details of a phenomenon more closely by slow-motion projection (or, rather, by making the exposure at increased frame-speed).

Though it would seem but a small step, in reality it presented almost insurmountable difficulties. To obtain the advantages mentioned it is usually necessary to make substantially more than ten exposures per second, and to do so continuously for a relatively long time, e.g. for half a minute. Since a fairly large quantity of radiation is required to take a single radiograph of organs such as the stomach, heart or lungs by the orthodox techniques, the making of a film entailed exposing the patient to an accumulated dose that could scarcely be justified. Moreover, it meant subjecting the X-ray tube to an extremely heavy load. The high dose of radiation required was due in part to the fact that to make such films the fluorographic method mentioned above, i.e. photography of the fluorescent screen was the only available method. The limited solid angle subtended by the light rays entering the camera, even with mirror cameras of very high light-gathering power, makes the situation about five times less favourable than with the same number of contact radiographs.

It is evidence of the importance attached to X-ray cinematography that, in spite of these drawbacks, experiments in this field[2] have been carried out for many years in a number of countries. Its application, however, was restricted to cases where the exposure of the patient to a very considerable dose of radiation could be regarded as the lesser of two evils. To obtain the necessary intensity of radiation from the X-ray tube, ingenious but intricate devices were evolved (e.g. rapid switching of the high tension on the tube in order to minimize unnecessary generation of heat at the anode).

---

[1]) See e.g. W. Hondius Boldingh, Mirror cameras for general X-ray diagnostics, Philips tech. Rev. 15, 58-65, 1953/54.

One of the greatest advantages resulting from the development of X-ray image-intensifiers is that it enabled the problem of cinefluorography to be tackled afresh and with considerable success. The primary fluoroscopic image is transformed by the image intensifier into an image of many times higher luminance. For the purposes of fluorography or cinefluorography much weaker primary images can therefore be used, and hence the X-ray intensity drastically reduced.

This possibility has been discussed in earlier articles in this journal and elsewhere on the applications of the first X-ray image intensifier developed by Philips [3][4]. This has an image field of 5″ (12.5 cm) diameter and gives a luminance intensification of 1000× or more. For cinefluorography with this image intensifier, use was initially made of a suitably adapted commercial 35 mm cine-camera. Later, 16 mm cameras were employed for the same purpose [5]. We shall return presently to the relative merits of 16 mm and 35 mm film for cinefluorography.

The apparatus referred to proved of great value for many examinations in X-ray diagnosis. From the very beginning, however, the relatively small field of view limited the usefulness of the apparatus. For filming the large organs, such as the heart and lungs, a larger field is necessary. To meet this need, Philips have developed in recent years an apparatus specially designed for cinefluorography, which employs a large image intensifier having an image field of *11″ (28 cm) diameter*. Various publications have already appeared on the medical application of this apparatus [6]. In this article we shall deal with the more important technical details.

Like the smaller version earlier described, the new image intensifier is of the electronic type; it consists of an evacuated tube in which the fluorescent X-ray image is converted into an electronic image. Although it is possible in principle to make intensifiers of this type for even larger image fields, e.g. for a field of 12″×16″ (30×40 cm) covering the whole thorax and capable of being used for normal fluoroscopic screens, we have not gone farther than the said diameter of 11 inches for fabrication reasons and also in order to avoid an unwieldy size of tube. (Recently an image intensifier of intermediate size, 9″, has been added to our range of current types.)

In this connection it is obvious to think of using solid-state image intensifiers (e.g. the "amplificon") whose operation depend on the phenomenon of electroluminescence and of which some basic forms have been described in an earlier article in this Review [7]. Work on the development of such devices is in progress in various parts of the world, but it will probably be many years before their principal limitation is overcome, namely their excessive inertia, which makes them at present unsuitable for cinefluorography.

Description of the apparatus

We shall begin by reviewing the installation, after which we shall discuss the principal parameters and the construction of the main components.

In the first place the apparatus contains the above-mentioned 11-inch image intensifier and a cine-camera fitted with a Schmidt mirror system of great speed. The image intensifier and the mirror camera are optically matched and contained in a cylindrical housing. In *fig. 1* this can be seen at the right, mounted on a stand. The patient is shown in this photograph positioned on a "Müller" UGX universal stand [8]. A "ring stand" specially developed for the cinefluorographic equipment is discussed at the end of this article. The X-ray tube is on the left in fig. 1, and behind it the high-tension generator. The control desk, which contains some special features for cinefluorography, is not shown.

---

[2] For the history of cinefluorography see the papers presented by F. Dessauer, R. Janker, R. Reynolds and H. van de Maele at the X-ray Congress held at Vienna in September 1936 (Fortschr. Geb. Röntgenstr. **56**, 126-142, 1937). The first paper deals, among other things, with the work of P.H. Eijckman, the Dutch pioneer of cineradiography, who made "synthetic" X-ray films ar early as 1903, and genuine X-ray films in cooperation with others in the years from 1908 to 1915. See also:
R. Janker, Roentgen cinematography, Amer. J. Roentgenology **36**, 384-390, 1936.
G. H. Ramsey, J. S. Watson, J. B. Steinhausen, J. J. Thompson, F. Dreisinger and S. Weinberg, Cinefluorography: a progress report on technical problems, dosage factors and clinical impressions, Radiology **52**, 684-690, 1949.
R. Janker, Apparatur und Technik der Röntgenkinematographie zur Darstellung der Herzbinnenräume und der grossen Gefässe (Angiokardio-Kinematographie), Fortschr. Geb. Röntgenstr. **72**, 513-520, 1950.

[3] M. C. Teves and T. Tol, Electronic intensification of fluoroscopic images, Philips tech. Rev. **14**, 33-43, 1952/53.

[4] J. Feddema, Medical aspects of the image intensifier, Philips tech. Rev. **17**, 88-93, 1955/56.

[5] See e.g. L. B. Lusted and E. R. Miller, Progress in indirect cineroentgenography, Amer. J. Roentgenology **75**, 56-62, 1956; G. M. Ardran and D. G. Wyatt, A portable X-ray cinecamera, Brit. J. Radiol. **30**, 52-54, 1957 (No. 1).

[6] R. Janker, Medicamundi **2**, 38, 1956 (No. 2) and Röntgen-Blätter **10**, 289, 1957.
G. J. van der Plaats, Fortschr. Geb. Röntgenstr. **86**, 1957, Beiheft, p. 54.

[7] G. Diemer, H. A. Klasens and P. Zalm, Electroluminescence and image intensification, Philips tech. Rev. **19**, 1-11, 1957/58.

[8] H. Verse and K. Weigel, A novel type of diagnostic X-ray unit, Philips tech. Rev. **17**, 138-145, 1955/56.

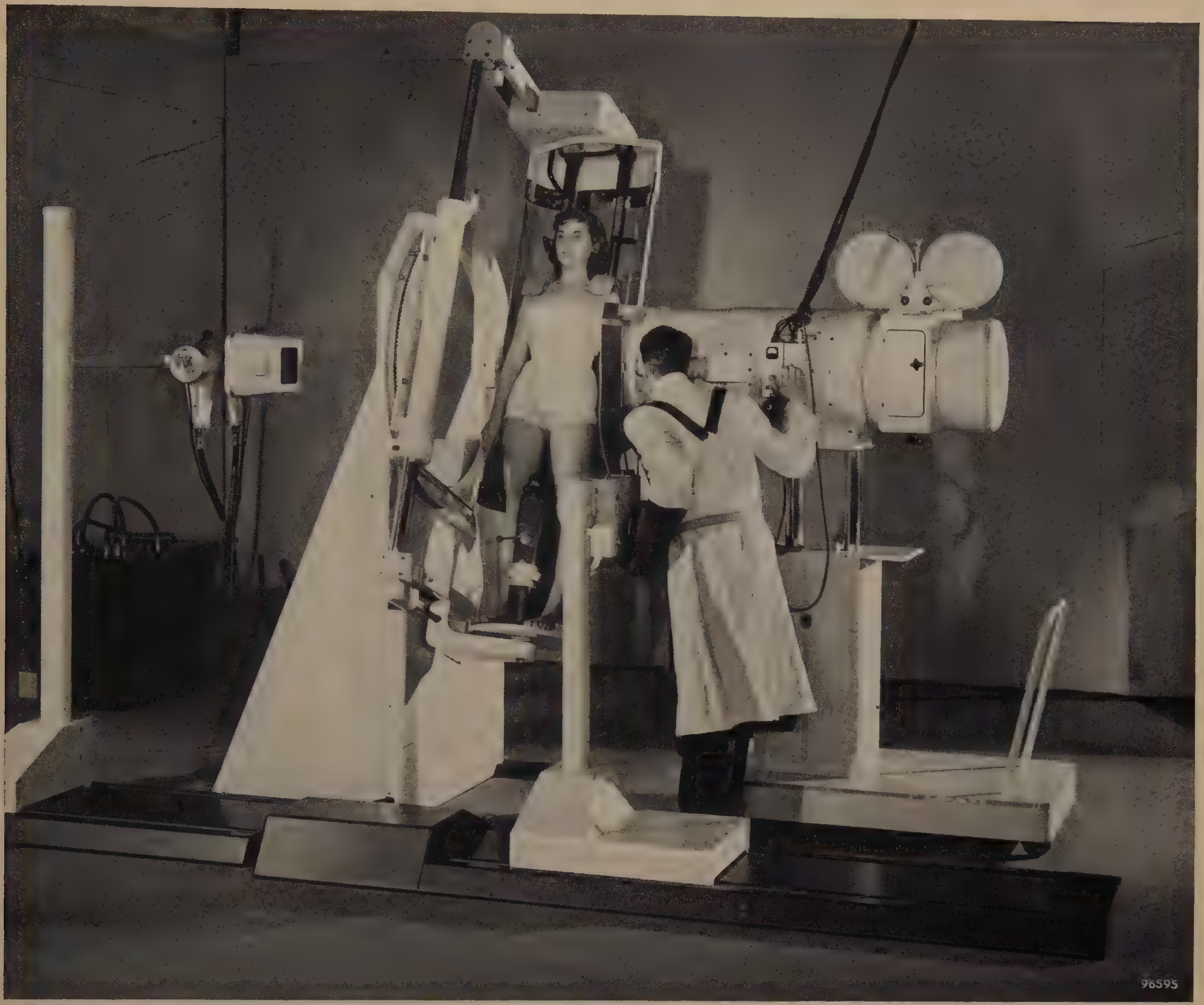


Fig. 1. Apparatus for cinefluorography with the 11-inch image intensifier. The patient is positioned here in a "Müller" UGX universal stand.

The 11-inch image intensifier gives a luminance intensification of at least 100×. The intensified image on the viewing screen can be viewed by two observers simultaneously through two optical systems mounted on the camera housing. These viewing systems are arranged in such a way that the patient remains within reach of the observer. At any appropriate moment during the fluoroscopic examination the radiologist can start filming by depressing a push-button (delay time only 0.2 sec). While filming he continues to watch the fluoroscopic image. This is of great practical importance, for one reason because the radiologist may wish to cause the patient to make or undergo various movements while the film is being made, the results of which he can now check on the viewing screen. With the aid of a photoelectric exposure meter the average photographic density (blackening) of the film can, if required, be kept constant irrespective of differences in X-ray absorption resulting from the movement or turning of the patient. A "heat integrator" can be incorporated in the X-ray apparatus to prevent excessive heating of the tube anode by unduly prolonged and heavy loading.

Films can be taken at a frame frequency ranging from 6 to 48 frames per second, adjustable in six steps. The film spools, visible above the camera housing in fig. 1, can accommodate 300 metres of film. The X-ray tube is operated for cinefluorography at a voltage between 50 and about 125 kV, as is usual in diagnostic practice; the tube current as a rule need not be higher than 20 mA.

Choice of picture size and splitting of the reduction factor

The situation of cinefluorography before the advent of the image intensifier is characterized by the fact that protagonists of this practice designed

70 mm cameras for the purpose [9]). Lack of light made it necessary to use an extremely sensitive and therefore coarse-grained film. For this reason a relatively large film size was important if detail perceptibility was not to suffer unduly from the graininess of the film. This applied particularly to the viewing of separate frames of the film strip, in which case no use is made of the property of the eye to integrate over a time of about 0.2 sec., i.e. over a number of successive frames. The advantage of 70 mm film in this respect was found to outweigh its drawbacks, namely that it called for a costly special optical system and that a 70 mm film cannot be directly projected with the standard projectors designed for 35 mm or 16 mm film. For the present apparatus, in which the light problem is much less acute and thus allows the use of finer-grained types of film, only the 35 mm and 16 mm sizes entered into consideration in view of the desirability of projecting the films with standard projectors. As regards the choice between 35 mm and 16 mm, the 16 mm size is attractive in that the films can be projected with amateur equipment, which is cheaper and in most countries is not subject to restrictive regulations. However, to reproduce all the information contained on the 11 inch screen the 16 mm film would have to be so fine-grained that it would be too insensitive for most diagnostic problems. For this reason we decided to adopt the 35 mm size.

The film gate in a standard 35 mm projector measures about 15×21 mm. The round image-field of the 28 cm image intensifier can therefore be reproduced, without significant losses, with a diameter of 18 mm. Thus, the image must be reduced in all by 15.5 times. The reduction is effected in two steps: the image intensifier produces on the viewing screen a reduced image of the primary fluoroscopic image (reduction factor r_1), and the cinecamera projects a reduced image of the viewing screen on to the film (reduction factor r_2). The condition $r_1 \times r_2 = 15.5$ leaves the choice of the ratio of the two reduction factors still open (distribution of the total reduction over image intensifier and camera).

It is useful to make the reduction factor r_1 of the image intensifier as large as possible, because the luminance intensification relies to a large extent on the electron-optical reduction [10]), and this is proportional to r_1^2. The resolving power of the electron-optical image projection and of the viewing screen would impose the only limitation on r_1, except that the cine-camera, whose reduction factor r_2 must be decreased as r_1 is increased, also imposes limitations.

As mentioned, the camera contains a Schmidt mirror optical system; the system used is of the type earlier developed for single-exposure fluorography [1]). It contains a mirror of 33 cm diameter and a correction plate of $D = 20.5$ cm diameter (diaphragm); the focal length f of the system is 17 cm. There are two reasons why it is useful to have the smallest possible reduction factor for such a system. In the first place it shortens the object-distance $v = (r_2 + 1)f$, which is responsible for most of the total length of the apparatus; see *fig. 2*. (The length of the image intensifier is only slightly altered by variation of the factor r_1.) In the second place, a smaller reduction factor means a larger aperture ratio $1 : N$ of the mirror system. This aperture ratio, which primarily determines the speed of the camera [11]), may be formulated generally as:

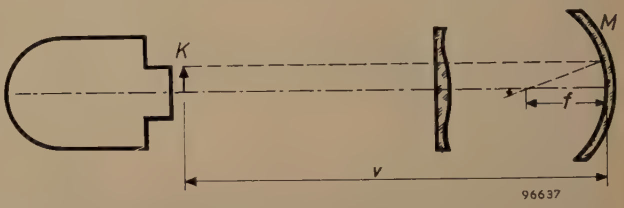


Fig. 2. Sketch showing the relative positions of image intensifier and mirror camera. The total length of the apparatus is largely governed by the object distance v (from viewing screen K to mirror M).

$$1 : N = \frac{D}{f} \frac{r_2}{r_2 - 1} . \quad . \; . \; . \; . \quad (1)$$

For values of r_2 equal to 10, 5 and 2.5, the factor $r_2/(r_2 - 1)$ has the values 1.1, 1.25 and 1.66, respectively.

The requirements with regard to r_1 and r_2 are thus nicely in harmony. Unfortunately, however, limitations are earlier encountered in the reduction of r_2 than in the raising of r_1. The most serious limitation consists in the fact that the reduction of r_2 brings the film holder increasingly farther away from the mirror and nearer to the correction plate. To avoid the constructional difficulties which this would entail, the lower limit of r_2 for the mirror camera has been fixed at 3.6. The reduction factor of the image intensifier is thus fixed at $r_1 \approx 4.5$ and the diameter of the viewing screen at about 60 mm.

---

[9]) J. S. Watson, S. Weinberg and G. H. Ramsey, A 70 mm cinefluorographic camera and its relation to detail, Radiology **59**, 858-865, 1952.
R. Janker and K. Einert, Röntgenkinematographie mit einer neu entwickelten Kamera für 70 mm breiten perforierten Film, Röntgen-Blätter 7, 51-58, 1954.

[10]) See article [3]), p. 35.

[11]) See W. Hondius Boldingh, Fluorography with the aid of a mirror system, Philips tech. Rev. **13**, 269-281, 1951/52.

Owing to the masking factor S of the mirror camera, a further reduction of r_2 would not entail much improvement in the light-gathering power of the optical system: the film holder, with the film gate, the rotary shutter and parts of the transport mechanism, inevitably intercept a part of the useful light proceeding towards the mirror, so that only a fraction S actually reaches the mirror. It can be seen from fig. 3 that this fraction is smaller the smaller the object distance, i.e. the smaller the reduction factor r_2; this partly destroys the gain in the aperture ratio.

After the above considerations it is necessary to return for a moment to the choice of a mirror system for the cine-camera. When used for fluorography, as earlier described 1), the mirror camera is required to project the image of a large object (a standard fluoroscopic screen) on to a certain small size of film, hence with a fixed reduction factor of about 6 to 10. For this purpose mirror optical systems have almost entirely superseded lens systems, since they combine a much greater speed with good image quality and a reasonable price. In our case, where a much smaller reduction factor is possible and desirable, this advantage of the mirror system carries less weight. This remains true even when the focal length is not taken as fixed (see above) but is chosen in relation to the other considerations. Our decision in favour of the mirror system was therefore prompted mainly by other factors, such as the relative ease with which a good image quality can be obtained, the large available space for viewing systems, etc., and by the considerable experience already gained by Philips in the development of mirror cameras for fluorography.

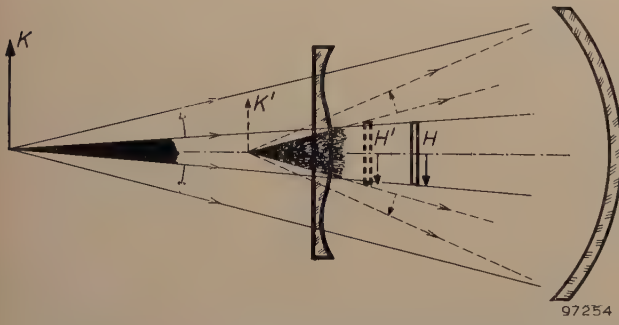


Fig. 3. For a given size of image (film size) the film holder intercepts a larger fraction of the useful beam of light the lower is the reduction factor K/H ($K'/H' < K/H$).

The 11-inch X-ray image intensifier

The operation of the 11-inch X-ray image intensifier is essentially similar to that of the smaller type earlier described 3). We shall briefly recapitulate it with reference to the schematic cross-section shown in *fig. 4*. The X-rays transmitted by the object impinge on the primary fluorescent screen R and excite it into bluish fluorescence. The fluorescent light liberates electrons from the photocathode F, which is in contact with the fluorescent screen and is mainly sensitive to blue light. The X-ray image is thus converted into an electron image: the photoelectrons are accelerated by an electrostatic field in the evacuated tube and at the same time focused to an electron-optical image of reduced size on a fluorescent screen K (viewing screen) in the anode A. The accelerating potential between photocathode and anode is 25 kV. The focusing electrode E, to which a variable voltage of 100 to 500 V is applied, makes it possible to adjust the definition of the image (i.e. to achieve the best compromise between central and peripheral sharpness).

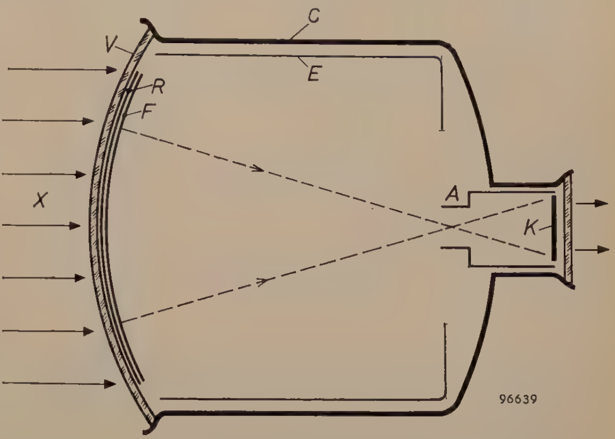


Fig. 4. Schematic cross-section of the 11-inch X-ray image intensifier. V glass window in front of primary fluorescent screen R, F photocathode, A anode, K viewing screen, E focusing electrode, C chrome-iron envelope.

The principal data of the large tube, some of which we have already mentioned above, are given in *Table I* side by side with those of the 5-inch tube. Various differences will be indicated in the following.

Table I. Particulars of the Philips 5″ and 11″ image intensifiers *).

	5″	11″
Diameter of useful image field	12.5 cm	28 cm
Electron-optical reduction factor	9.5	4.5
Luminance intensification	≧1000	≧100
Resolving power (lines/cm):		
in middle of primary fluorescent screen	30	22
at the edges of primary fluorescent screen	20	15
Smallest perceptible contrast	4%	6%

*) The large tube is a version, specially modified for cinefluorography, of an 11-inch image intensifier developed by Philips Electron Tubes Division in 1953. This tube, like its 5-inch predecessor, had a reduction factor of approx. 9.5.

Outwardly the most striking difference between the two tubes is that the large tube, because of its greater size, is made largely of metal, i.e. of chrome-iron (*fig. 5*). Experience gained with chrome-iron/glass vacuum seals in the fabrication of television picture tubes played of course an important part in the design of this tube. The X-rays enter the tube through a convex glass window with

---

12) Philips tech. Rev. 14, 281, 1952/53.

which, in this case, the primary fluorescent screen is in direct contact. Sealed into the base of the tube at the opposite end is an optically flat viewing window. The X-ray window must be thick enough to withstand atmospheric pressure and shocks, although not thicker than is strictly necessary, in order not to attenuate the X-rays excessively. For the same reason the glass chosen had to be a type containing the fewest possible elements of high atomic weight. Furthermore the composition of the glass had to be such as to ensure a good seal to chrome-iron. With the glass employed the X-ray transmission amounts to 60% for the window of the large tube and 90% for that of the small tube, both measured at a voltage of 90 kV on the X-ray tube and with a filter of 20 mm Al (approximately equivalent to the thorax).

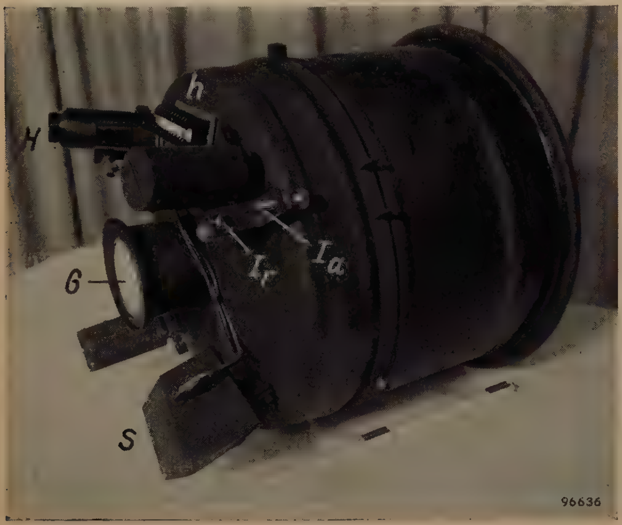


Fig. 5. The 11-inch X-ray image intensifier. *G* glass window in front of viewing screen, *H* high-tension connection (25 kV), *h* terminal block for other connections, *S* ionization gauge and pump, I_r one of the three radial adjusting screws, I_a one of the three axial adjusting screws.

In an earlier article on the 5-inch image intensifier various effects were described that cause slight blurring of the image. One cause of blurring is the X-radiation which is scattered in the window or, having passed the X-ray screen, on the tube walls. The fluorescent light, too, insofar as it is not absorbed by the photocathode, can cause image blur as a result of diffuse reflection from the tube walls. The first effect is somewhat greater in the large tube owing to the greater thickness of the X-ray window (more scattered X-radiation). Nevertheless, the total loss of contrast is not very significant, as appears from the value of 6% given in the above table for the smallest perceptible contrast (in light as well as in dark parts). The *reproduction* of the contrasts present in the X-ray image can always be appreciably improved photographically as compared with the observed image by using a high-gamma film.

A difficulty arising from making the tube largely of metal is that gases are released from the walls during the life of the tube. If their pressure exceeds a certain value, e.g. 10^{-5} mm Hg, a grey spot will develop in the centre of the viewing screen, which may prove troublesome. This is caused by ion bombardment of the centre of the photocathode, as a result of which photoelectrons are liberated and in turn accelerated towards the anode. The metal parts cannot be completely degassed during fabrication since it is not possible to raise the temperature during pumping to a high enough value. The solution found for this problem was to fit an "ion pump" to the image intensifier tube. This pump is simply an ionization gauge in which the gas molecules emerging from the tube are ionized and accumulated in an ion collector [13]). The supply voltage for this pump, approximately 2000 V, is tapped from the high-tension generator which supplies the 25 kV accelerating voltage. The ion pump also serves as a gauge to measure the pressure in the tube. The pressure indication is used for controlling a safety device, which prevents the high-tension from being switched on when the tube pressure it too high.

To avoid having to refocus the cine-camera on to the viewing screen if the tube should have to be replaced — which would be a very laborious process — the tube is provided with six adjusting screws by means of which the tube location is prefocussed during manufacture. Three screws (see fig. 5) are in the axial direction and are so adjusted that their stop faces lie in a certain plane parallel to the viewing screen, with an error of less than 0.1 mm. The housing in which the tube and camera are mounted is provided with a thrust surface perpendicular to the optical axis of the whole assembly. By means of a sprung suspension system the tube with its three stop faces is pressed against this thrust surface, so that the viewing screen lies exactly in the object plane of the mirror camera. Analogously, with three preset radial adjusting screws and a cylindrical surface in the housing, the centre of the viewing screen is correctly aligned, the deviation amounting to no more than 0.5 mm.

Cinefluorographic camera and accessories

Light-gathering power and resolving power

Some details of the optical system of the mirror camera have already been touched on in the foregoing, viz. the diameter of the mirror = 33 cm, diameter D of the diaphragm = 20.5 cm, focal length f = 17 cm, reduction factor r = 3.6. With these data the aperture ratio is found from equation (1) to be $1 : N = 1 : 0.60$. The effective aperture ratio is smaller, because the camera housing, the shutter etc. intercept part of the light entering the camera, amounting in our case to about 50% (masking factor 0.5). This gives:

---

[13]) See e.g. Philips tech. Rev. **20**, p. 145, 1958/59 (No. 6).

$$1 : N_{\text{eff}} = 1 : 0.83\,,$$

which is an extremely high value, corresponding approximately to the highest values obtainable with mirror cameras in single-exposure fluorography.

A proper appreciation of the light-gathering power of the camera must also take into account the image quality and factors extraneous to the camera such as the properties of the X-ray screen and the film material, which partly determine the quantity of X-radiation needed for a single frame. This, after all, is the quantity which matters.

As regards image quality, a very favourable circumstance is that the optical system need only have a small field of view, namely 7°. This is due to the relatively large focal length and to the small dimensions of the viewing screen. For comparison it may be mentioned that fields of view of about 30° are needed in single-exposure fluorography. Even with the Schmidt mirror camera, which, compared with other optical systems, lends itself particularly well to the sharp focusing of large fields of view, difficulties are experienced where such large angles are concerned. For technical purposes an image of adequate sharpness, both at the edges and in the centre, can be obtained up to 25°, but at 30° some central sharpness must be sacrificed in order to improve the definition at the edges, by slightly modifying the shape and position of the correction plate. The only way to avoid this is to use more complicated optical systems, as for example a mirror camera with three correction plates instead of one, or with a correction element and a so-called conical lens [14]).

These complications, then, do not arise with the present cinefluorographic camera, and full attention could be concentrated on obtaining the sharpest possible definition in the centre of the small field of view. As a result the camera is capable of resolving some 110 lines per cm on the viewing screen.

In practice this means that the resolving power is limited not by the camera but almost invariably by the graininess of the film. With a sensitive fluorographic film (Gevaert Scopix, Agfa Fluorapid) the resolution is equivalent to about 60 lines/cm of the viewing screen. With slightly less sensitive but finer-grained emulsions, made experimentally by Gevaert, Agfa and Kodak, a resolution equivalent to 75 lines/cm has been achieved, still keeping the dose to the patient relatively low. This fine-grained film yields no advantage as far as observing a projected moving picture is concerned, because then, owing to the integrating power of the eye, a resolving power equivalent to 75 lines/cm is also obtained with coarse-grained film, and the integration with the fine-grained film offers no further improvement.

Finally, if we compare the X-ray energy needed for a single image produced by different radiographic methods, we arrive at the following ratios (these rough figures also depend to some extent on the X-ray tube voltage and on the filter employed, since the methods have different spectral sensitivities). Let the energy for a normal direct exposure be 1 (using intensifying screens of average luminous intensity), then the energy required with our cinefluorographic apparatus is 0.02 to 0.03; for cinefluorography with the 5-inch image intensifier and a tandem optical system, earlier described [15]), about 0.015 to 0.02; and for normal single-exposure fluorography about 3 to 5. (All these values presuppose the use of a scatter grid, though this will not usually be necessary with the 5-inch image intensifier.) In spite of the difference in energy, the load on the X-ray tube is virtually the same for both cinefluorographic systems, the camera for the 11-inch image intensifier having been provided with a 1.5 times larger shutter opening, viz. 270° instead of 180°. This entailed no particular problems because a Maltese cross mechanism is used for the film-transport of this camera (see below).

From the figures mentioned, and from the numerous exposure data already published (see e.g. [4])), it can be concluded that with X-ray equipment capable of sufficiently high voltages (125 kV) it is now possible to film all objects in the human body, even relatively large organs, without exposing the patient to an unjustifiably large dose of X-radiation (see *Table II*).

The viewing system

The cross-section in *fig. 6* shows the construction of the optical system by means of which two observers can view the image while the film is being made. The eyepieces are mounted at opposite sides of the image intensifier close to the patient, and are so aligned that the observers have the impression of looking towards the X-ray screen (fig. 1). This positioning is made possible by deflecting the path of the rays in each viewing system by means of four plane mirrors. The observers see the image almost upright and at somewhat more than half its true size. The first mirror of both viewing systems is situated near the optical axis of the camera. These mirrors are kept small enough to lie almost entirely within the cone of the rays which are incident on the back of the film-holder, and which thus have no part in the exposure. By thus limiting the size of the mirrors the light-gathering power of the camera is unimpaired, though of course this is at the expense of the brightness of the *observed* image. This is also adversely affected by the losses due to the multiple reflections. Nevertheless the brightness obtained is more than adequate. A further contributory factor is that the viewers are designed with an exit pupil of 5 mm, which is larger than the entrance pupil of a normal adult eye.

---

[14]) A. Bouwers, Improvement of resolving power of optical systems by a new optical element, Appl. sci. Res. **3B**, 147-148, 1953.

[15]) P. M. van Alphen, Optical aids for the image intensifier, Philips tech. Rev. **17**, 77-83, 1955/56, especially p. 82.

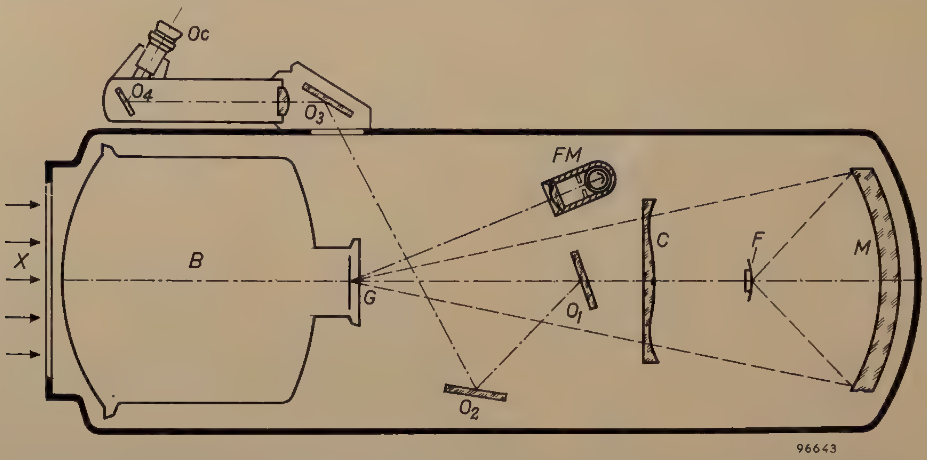


Fig. 6. Simplified horizontal section through the housing of the cinefluorographic apparatus. *X* X-rays, *B* image-intensifier tube with viewing window *G*, *M* spherical mirror and *C* correction plate of cine-camera, *F* film, O_1-O_2-O_3-O_4 mirrors and *Oc* eyepiece of viewing system (for simplicity only one of the two viewing systems is shown), *FM* photomultiplier with lens and diaphragm for measuring the luminance of the viewing screen.

Table II. Some typical operating data and patient doses for films made with the cinefluorographic apparatus, at a frame-frequency of 16 frames per sec and employing a cine-film of sensitivity comparable with 100 A.S.A. *)

Body part	Tube voltage (kV)	Tube current (mA)	Distance from focus to image intensifier (cm)	Focus-skin distance (cm)	Skin dose with 2 mm Al extra filter (r/min)
Maxilla	70	10	100	80	2.5
Cervical spine, lateral	70	6	100	80	1.5
Oesophagus, at pharynx level	80	4	100	80	1.5
Oesophagus, at thorax level	100	8	80	50	10
Stomach, antero-posterior	125	9	80	50	16
Small intestine	125	9	80	50	16
Kidneys	100	9	80	50	12

*) These exposure data are merely a rough guide, since they depend upon other factors such as object thickness, scatter grid, film-processing technique, etc.

The photometric system

The average luminance of the viewing screen of an image intensifier can, in principle, be very simply determined by measuring the current through the tube, this being a measure of the total number of photoelectrons passing from the X-ray screen to the viewing screen, and hence — for a given area of the viewing screen — a measure of the average luminance.

This method is in fact used with the 12.5 cm image intensifier. However, for the 28 cm type it is less suitable because the object under examination will often not entirely cover this larger X-ray screen. To avoid exposing the patient to unnecessary X-radiation, and also to reduce scatter, it will then sometimes be desirable to stop down the X-ray beam. In that case the area of the viewing screen over which the average brightness is to be determined will vary, thus complicating the measurement. If the X-ray beam is not stopped down the too bright or too dark peripheral parts of the screen may give misleading results when using this method of measurement.

For this reason a system was chosen whereby the luminance of the viewing screen is directly measured. Only in the central part of the screen is the luminance measured: except in very few cases, this is always covered by the image. The system uses a photo-multiplier tube with a lens and diaphragm (see fig. 6). The lens forms an image of the viewing screen on the plane of the photocathode in the multiplier tube, and the diaphragm limits the effective image to a circle equivalent to 22 mm diameter on the viewing screen (or 10 cm on the primary fluorescent screen). This diaphragm can be changed if a different field limitation is better suited to the work on hand. A frosted glass plate in contact with the diaphragm eliminates the effect of any local differences in the sensitivity of the photocathode.

The electric signal which the photomultiplier tube delivers as a measure of the screen luminance is read on a meter. The use made of this information during the making of the film will be discussed presently.

Mechanism of the cinefluorographic camera

The films are recorded on standard perforated 35 mm film. Since the object to be filmed appears as an inverted image on the viewing screen, the film must be transported from bottom to top, instead of in the usual direction from top to bottom; when normally projected the object then appears upright.

The film mask is matched to the viewing screen: it is round and, as mentioned, has a diameter of 18 mm, which is reasonably suited to the standard dimensions, 15.2×20.9 mm, of the film mask in normal 35 mm projectors. Only 7.2% of the image is lost through projection cut-off, whilst the image is 40% larger than if the diameter 15.2 mm had been selected. This is of particular importance for the quality of the image when individual frames are examined. It is also possible in principle to enlarge the mask of a normal projector so as to lose nothing of the round image of 18 mm diameter (the frame pitch of 35 mm film is 19 mm).

The mechanism of the film-transport system is shown schematically in *fig. 7*. The sprocket (*3*) responsible for the intermittent movement of the film is actuated by a Maltese cross. Particularly at high frame-frequencies, this ensures more reliable transport of the film and causes less wear of film and moving parts than the claw mechanism usually found in cine-cameras. Moreover, with the normal (four-slot) Maltese cross the actual frame-shift period is not longer than $^1/_4$ of the total available time per frame, so that the aperture angle of the rotating shutter can be made 270° without any additional special measures. The asynchronous motor for the film transport mechanism has two speeds, and the film transport spindle is driven via a three-speed gear box, thus making it possible to obtain the six frame frequencies earlier mentioned, from 6 to 48 frames per second. The film can also be transported in reverse for subtitling and other special purposes. The shutter aperture being 270°, the exposure time varies from $^1/_8$ sec (at 6 frames per sec) to $^1/_{64}$ sec (at 48 frames per sec). The motor is kept running during the screening preparatory to cinefluorography. When the apparatus is switched over for cinefluorography, an electromagnetic clutch brings the transport spindle into motion with a delay not exceeding 0.1 sec.

As in the fluorographic mirror cameras earlier described [1]), the film is pressed against the film gate by a spherical pressure plate (*5*, fig. 7). This is necessary because in the Schmidt mirror optical system the image surface on to which a flat object is projected is spherically curved (concentrically with the mirror). Even without this condition a pressure plate would still be required, because the very large angle subtended by the mirror at the film (about 100°) necessitates extremely accurate positioning of the sensitive area of each frame — irrespective, for example, of the thickness of the film. The mechanical deformation produced by the spherical plate is easily tolerated by the film, and the image distortion after the return of the film into a flat plane is negligible. In view of the high frame-frequencies used, the spherical pressure plate cannot be designed — as it is in single-exposure cameras — to disengage the film during the transport. To ensure that the film is pulled through smoothly it is therefore necessary to pay very careful attention to the design of the pressure guides of the film gate. Moreover, with some types of film, the film gate will have to be cleaned more frequently to remove flaked emulsion than in normal cine-cameras. Little trouble will be experienced, however, if films with hardened emulsion are used.

In cinefluorography use is sometimes made of a lead shutter which is rotated in front of the X-ray tube window to protect the patient from X-radiation during the intervals in which the film is being pulled forward and hence cannot be exposed. The rotation of this lead shutter must of course be very accurately synchronized and in phase with the shutter in the cine-camera. The two shutters can be coupled for this purpose by means of a magslip or synchro: a synchro is fitted to the shaft of the asynchronous motor that drives the film and connected to another synchro on the spindle driving the lead shutter. The synchro on the motor shaft also makes it possible to run a second cine-apparatus synchronously with the first; this technique is in fact applied, for example when it is desired to make simultaneous frontal and transversal cine-exposures of a patient.

The large spools, which hold 300 metres of film, have the advantage that the film does not have to be changed so frequently. Supply and take-up spools are driven in the usual way via a friction clutch. Moreover the supply spool is provided with an automatic run-back device, which, at the end of an exposure, takes up the loop caused by the slight over-run of the heavy supply spool. This device is necessary to avoid the risk of film breakage, particularly at a high frame-frequency (48 frames per sec): a loop in the film would allow the transport mechanism to reach full speed while the supply-spool drive was still slipping slightly, so that, at the end of the loop, the film would be jerked violently from the spool.

Since the use of large spools means that the film remains longer on the supply spool and is thus exposed in some measure to secondary X-rays, the film magazine is covered with a lead shield. This sufficiently protects the most sensitive film material against fogging, even when the X-radiation is relatively hard (generated by 125 kV).

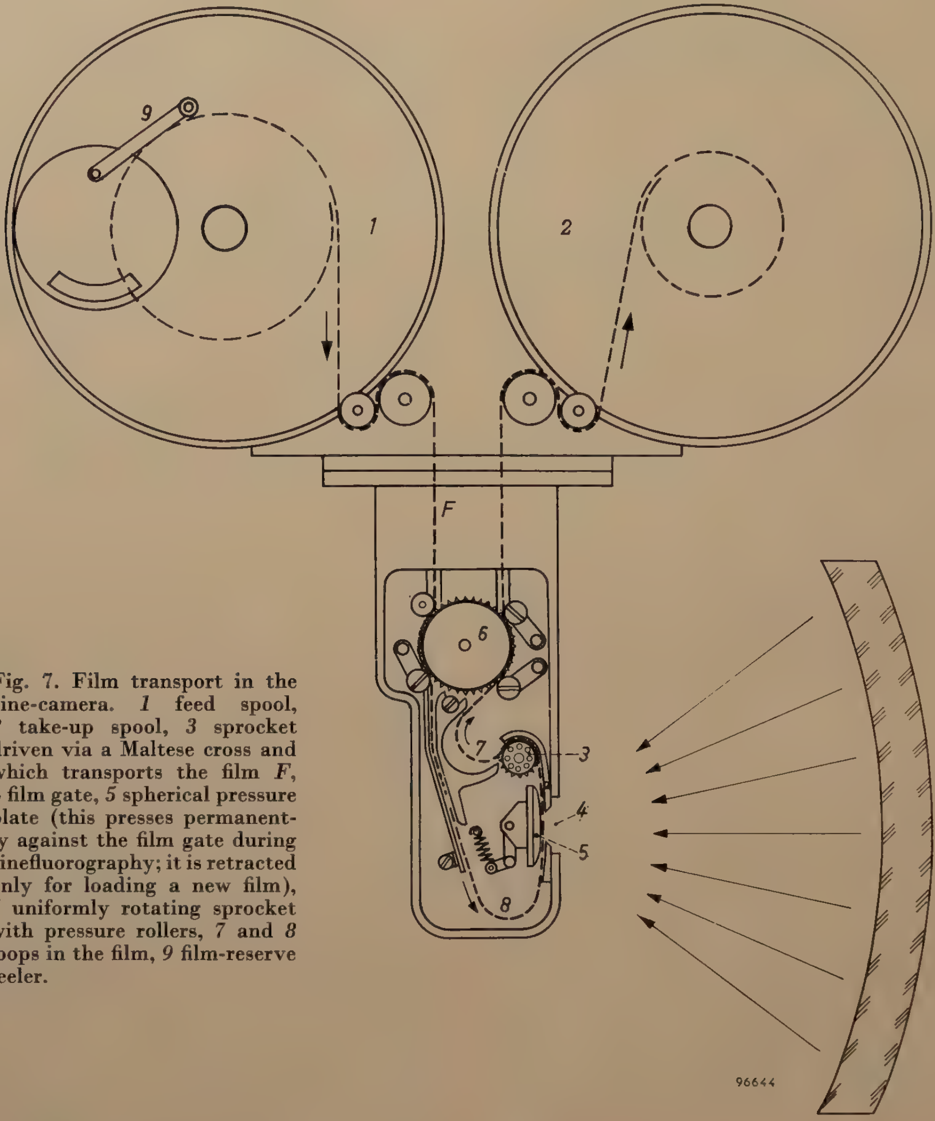


Fig. 7. Film transport in the cine-camera. *1* feed spool, *2* take-up spool, *3* sprocket driven via a Maltese cross and which transports the film *F*, *4* film gate, *5* spherical pressure plate (this presses permanently against the film gate during cinefluorography; it is retracted only for loading a new film), *6* uniformly rotating sprocket with pressure rollers, *7* and *8* loops in the film, *9* film-reserve feeler.

Special features of the X-ray equipment

In the installation here described the power supply for the X-ray tube is required to meet demands entirely different from those imposed in normal X-ray diagnosis. Although the tube tensions are the same (up to about 125 kV), the tube currents needed are much lower, usually being not more than 20 mA against 100 to 500 mA in normal diagnosis, whereas the total exposure times are very much longer, e.g. 10 to 100 seconds against the normal $^1/_{100}$ to a few seconds. The longer exposure times make it necessary to take careful account of the maximum permissible load on the X-ray tube, the limit in this case being set not by the temperature of the focal spot but by the temperature of the anode as a whole (except when a very small focus is used, e.g. 0.3 mm). In order to film as long as possible without approaching this load limit it is as well to operate the X-ray tube on direct voltage (for example by smoothing with capacitors the rectified voltage from the high-tension generator). For a given total quantity of X-radiation the required electrical energy, and hence the heat generated in the anode, is then as low as possible. Furthermore the use of direct voltage obviates stroboscopic effects even with varying frame frequencies, whereas with a pulsating supply it would be necessary to adopt complicated measures to counteract such effects, particularly at 48 frames per second.

The time switch employed in X-ray diagnostic apparatus for presetting the duration of the load on the tube (and hence the exposure time) is not needed for the cine-apparatus. The switch used for starting the film transport also switches on the X-ray tube for as long as the film is running. To be more exact, it brings the tube load up to the required value, for the X-ray tube will generally be operating at a low current, about 1 mA, before filming starts, in order that the radiologist can adjust the X-ray image and ascertain fluoroscopically the suitable moment to begin filming. Thereupon the tube current must be raised from the fluoroscopic value to the correct value for filming as rapidly as possible. A limit is set here by the thermal inertia of the filament in the X-ray tube, but the density stabilizer, which we shall now discuss, limits the transition time to an average of 0.1 sec.

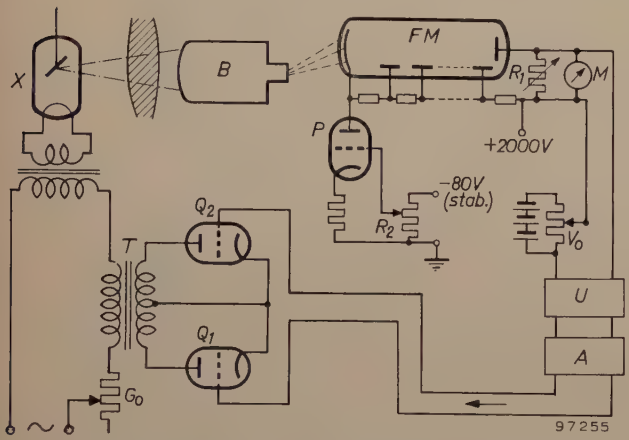


Fig. 8. Circuit diagram of density stabilizer. The filament voltage of the X-ray tube X is supplied via the primary of a transformer T, whose secondary is loaded by the triodes Q_1 and Q_2 which together constitute a variable impedance. The grid voltage on the triodes thus influences the impedance of the primary of T in the filament circuit of the X-ray tube. The output signal of the photomultiplier FM, which faces the viewing screen of the image-intensifier tube B, controls the grid voltage of Q_1 and Q_2 — and hence the current through the X-ray tube — in such a way that the deflection of the meter M, which is a measure of the observed luminance of the viewing screen, remains virtually constant. For this purpose the direct voltage produced by the photo-current across R_1 is compared with the very constant voltage V_0, and the difference (after conversion to alternating voltage in U and amplification in A) is applied to the grids of Q_1, Q_2. The required degree of blackening can be preset by adjusting the reading of M to the desired value (e.g. in the middle of the scale), by adjusting V_0.

Variation of R_1 thus means that the mean blackening is stabilized at different *viewing-screen luminances*, and a similar effect is produced by variation of R_2, which changes the supply voltage (stabilized by triode P) to the photomultiplier tube. The constant reading of M can now be made to correspond to a certain required *film-blackening* by adjusting R_1 in accordance with the frame-frequency selected (control range 1 : 8) and by adjusting R_2 to accord with the film sensitivity (control range 1 : 10).

G_0 can be adjusted to limit to a specified value (55 to 60 mA) the maximum filament current for the X-ray tube (which occurs, for example, if the image intensifier is inadversely switched off). The filament current can be regulated between about 0.3 and 50 mA.

The above-described photoelectric luminance meter, which is mounted in the camera housing, delivers an electrical signal which can be read from a meter on the control desk. This reading, taken in conjunction with the sensitivity of the film and the frame-frequency in use, makes it possible to adjust the required tube current (and if necessary the tube voltage) before beginning the actual examination. Moreover, a facility is provided for coupling the circuit of the luminance meter to the filament cur-

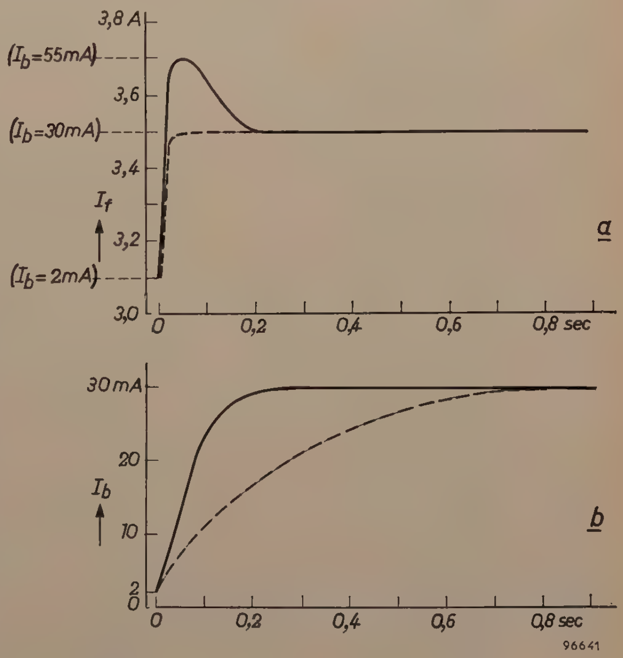


Fig. 9. *a*) Filament current I_f, *b*) tube current I_b of X-ray tube as functions of time after switching over from fluoroscopy to cinefluorography. If I_f were simply raised from the fluoroscopic value 3.1 A to the new value required, e.g. 3.5 A (for a tube current of 30 mA), then I_b would need about 0.8 sec to reach the steady value (dashed curves). The density stabilizer, however, causes the filament current initially to overshoot to the maximum possible value 3.7 A for as long as the screen luminance is still inadequate, so that the required tube current (and hence the required film blackening) is reached much earlier (solid curves). Care must of course be taken in the design of the circuit to ensure that the overshoot does not lead to oscillation.

rent circuit for the X-ray tube; the output signal from the photomultiplier then controls the tube current in such a way as to oppose variations in exposure, and hence in the average density (blackening) of the film. This density stabilization has proved to be extremely useful in cinefluorography in cases where it is important to move the patient during the film, which can give rise to considerable variations in X-ray absorption. (Sometimes automatic density regulation may be undesirable, e.g. where large shifts of the contrast medium are to be observed; for such cases manual control remains possible.) *Fig. 8* shows a simplified diagram of the stabilizer; the diagram also illustrates how changes in film sensitivity and frame-frequency are allowed for. The above-mentioned shortening of the transition time at the start of filming is due to the fact that, when the tube current suddenly has to be increased to produce a certain photographic density, the stabilizer does *not* raise the filament current immediately to the new steady value (the regulator is not "aware" of this value until the state is steady again) but raises it to a much higher value than the steady one for as long as the luminance on the viewing screen is still inadequate. This is explained in *fig. 9*.

A feature of cinefluorography that is unusual compared to normal cinematography is that the radiologist does not usually fix the length of the film beforehand, but lets it depend on what he observes through the viewing system while the film is being made. This implies that measures must be taken to avoid exceeding the permissible duration of the load corresponding to the selected values of tube voltage and current. The situation is made more complicated by the fact that the tube current, as we have seen, does not always remain constant during filming; moreover the film may be preceded by a period of screening, or periods of screening and filming may follow one upon the other, possibly punctuated by intervals of rest. It is then very difficult to apply the normal nomogram used by radiologists which gives the permissible combinations of voltage, current and loading time for given conditions of operation and cooling. We have therefore designed a kind of analogue computer (a "heat integrator") which, during operation, continuously integrates the electrical energy from the current and voltage in a way that takes account of the heating effect of each period of energy dissipation in the anode and also of the cooling during the intervals of rest and during operation (cooling by anode radiation). The principle of the circuit is explained in *fig. 10*. The result of the integration is read on a meter; the reading, which is now a direct measure of the anode temperature, can be compared with the maximum permissible total load (the maximum temperature) marked on the scale of the meter, thus providing a continuous indication of how far it is still possible to go. When the maximum load is reached the high tension is automatically switched off, so that the apparatus can be operated for as long as possible without the risk of inadvertently overloading the X-ray tube.

In addition to the stabilization of the film density and the safeguarding of the X-ray tube, a facility will in many cases be required for directly checking on the dose of radiation received by the patient during cinefluorography. For this purpose an ioniza-

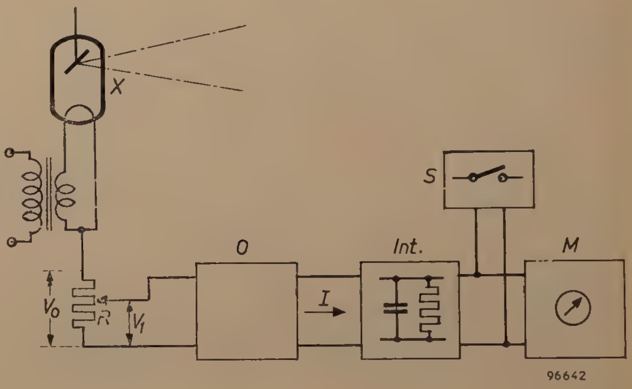


Fig. 10. Block diagram of the heat-integrater computer for safeguarding the X-ray tube against overloading. The voltage V_0 across the resistor R is proportional to the tube current. From V_0 a fraction $V_1 = aV_0$ is tapped off by the sliding contact on R. The sliding contact is coupled to the knob for controlling the tube voltage such that a is proportional to the latter. Thus, at any given instant, V_1 is a measure of the power dissipated at the tube anode.

The integration of this power is based on the fact that the supply and simultaneous dissipation of energy at the anode can be represented approximately by the charging of a leaky capacitor (i.e. with a resistor shunted across it). For this purpose the voltage V_1 is converted in circuit *O* into a charging current *I*, which is fed to an *RC* circuit denoted by "*Int*". When the capacitor is charged up to a predetermined value, read on the meter *M* — the "switch-off voltage" — the anode has then accumulated the maximum permissible quantity of heat; filming is then automatically stopped by switch *S*.

The circuit *O* is so designed that the charging current *I* varies according to a certain function of V_1. This function is found by selecting the current *I* for each value of V_1 (considered constant) such that the capacitor, starting at zero voltage, reaches the "switch-off" value after a period that corresponds exactly to the maximum loading time (found from the tube nomogram) associated with the relevant power (corresponding to V_1). Tests have shown that, even with varying power and intervals of rest, the total time taken to reach the switch-off voltage is correct to within a close approximation.

Since the tube nomogram applies to a particular size of tube focus, two individual circuits *O* have been designed on the basis of the nomogram data for two different foci. If the tube load is switched over from one focus to another, the correct circuit *O* automatically comes into operation (and the switch *S* is automatically set to the switch-off voltage applicable to that focus).

The switch *S* prevents further loading of the X-ray tube until the voltage on capacitor *C* has dropped to 80% of the switch-off value.

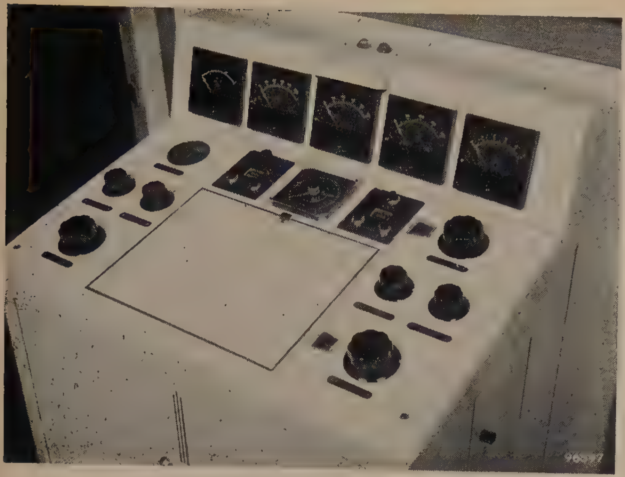


Fig. 11. Control desk for the cinefluorographic apparatus. The five meters, from right to left, indicate: the tube current, the film blackening to which the stabilizer is preset, the cumulative dose received by the patient, the cumulative load on the tube anode, and the supply voltage for the whole equipment. This voltage is corrected to the nominal value with the large knob bottom left. The two knobs above this serve to adjust the density stabilizer to the appropriate frame-frequency and film sensitivity. A clock under the meter in the middle indicates the filming time. The knob bottom right controls the tube voltage, the two above it control the tube current for fluoroscopy and cinefluorography, respectively, and the knob top right is the focus selector.

tion chamber can be placed in the X-ray beam, and the ionization current integrated by an amplifier circuit. The result of the integration, which is a

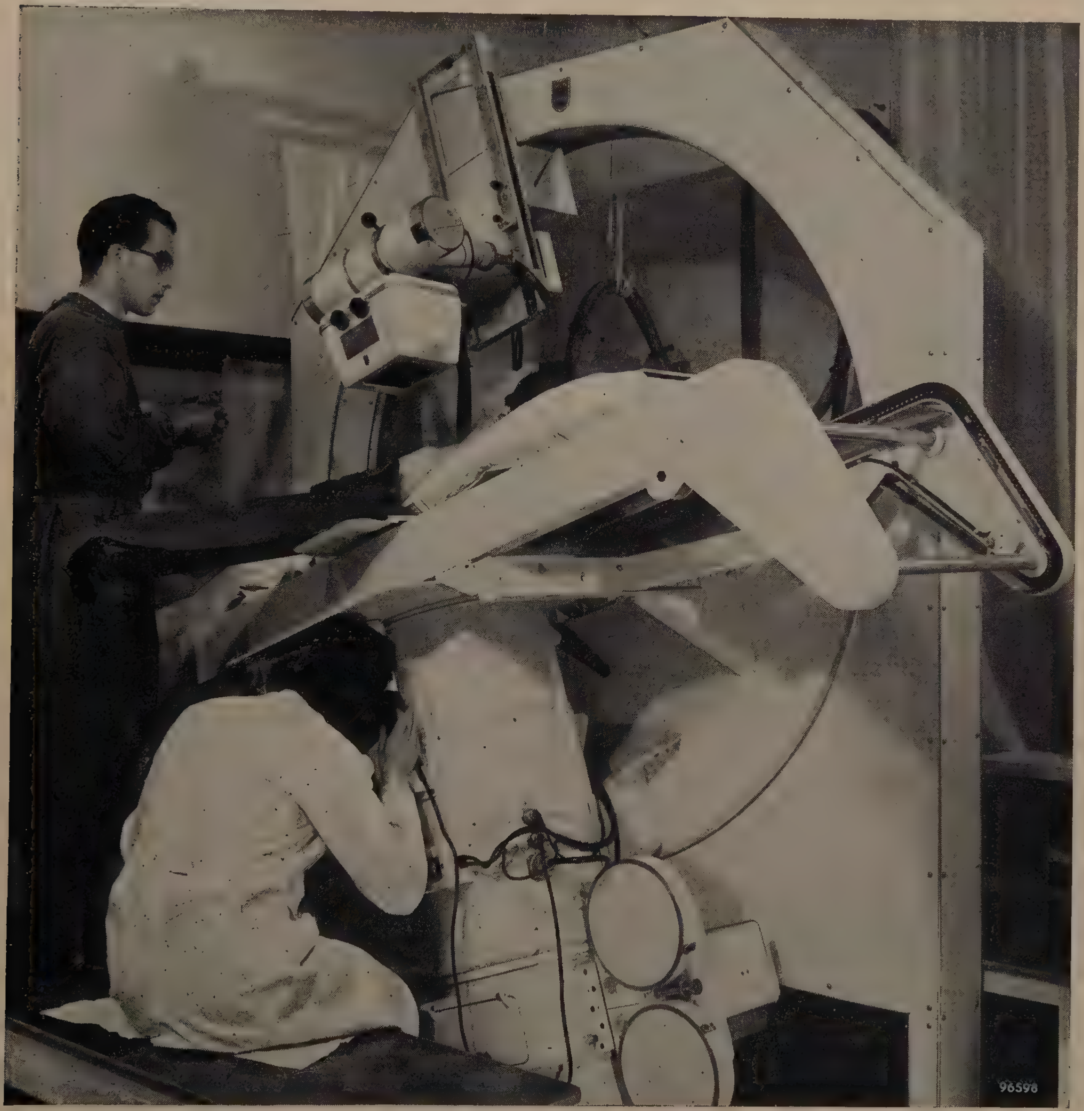


Fig. 12. "Ring stand" for cinefluorography. The X-ray tube (top) and the cinefluorographic equipment (below) are mounted on the ring such that the X-ray beam traverses a diameter of the ring. The part of the patient's body to be filmed lies virtually in the centre of rotation. Rotation of the ring tilts the patient into any desired position without altering his positioning in relation to the X-ray beam.

measure of the total dose in röntgens delivered by the tube at a particular distance, can be read from a meter on the control desk. At the same time the clock on the control desk indicates the total filming time.

The meters mentioned can be seen in *fig. 11*, which shows a photograph of the control desk for the cine-fluorographic apparatus. The X-ray tube and the high-tension generator can also be connected to a normal control desk, so that they can be used without the cine-camera for the purposes of conventional X-ray diagnosis.

Application of the apparatus

The considerable size and weight of the combination of the 11-inch image intensifier with a cine-camera make it impossible to mount this equipment on one of the normal stands used in X-ray diagnosis. A simple solution to this problem is offered by the "Müller" UGX stand (fig. 1), earlier described in this journal, and which was designed especially to meet the requirements imposed by the growing bulk of the viewing systems and attachments now coming increasingly into use [8]). This stand is indeed highly suited to many applications of cinefluorography. The simplicity of the UGX stand was obtained, however, by abandoning a conventional and widely used method of examination, namely the method of vertically irradiating a patient lying on his back, while possibly tilting the patient together with the X-ray beam about a horizontal transverse axis. To provide the radiologist with this facility, which is essential in certain diagnostic methods such as angiocardiography (examination of the heart vessels), a special stand has been designed for the 11-inch image-intensifier cinefluorographic equipment, based on the work of Janker [6]). It consists of a fixed frame containing a vertically mounted ring which rotates in its own plane. The frame is very rigidly mounted on base plates and supported on one side by two wall brackets. The ring carries the X-ray tube and the cine-apparatus, with the optical axis lying along a diameter of the ring, and between them is mounted the examination table; see *fig. 12*. The X-ray tube can be shifted along the ring diameter to vary the focus-screen distance. The centre of rotation of the ring is at a height of 165 cm above the base plates. Thus, the table and the cine-apparatus remain clear of the floor during

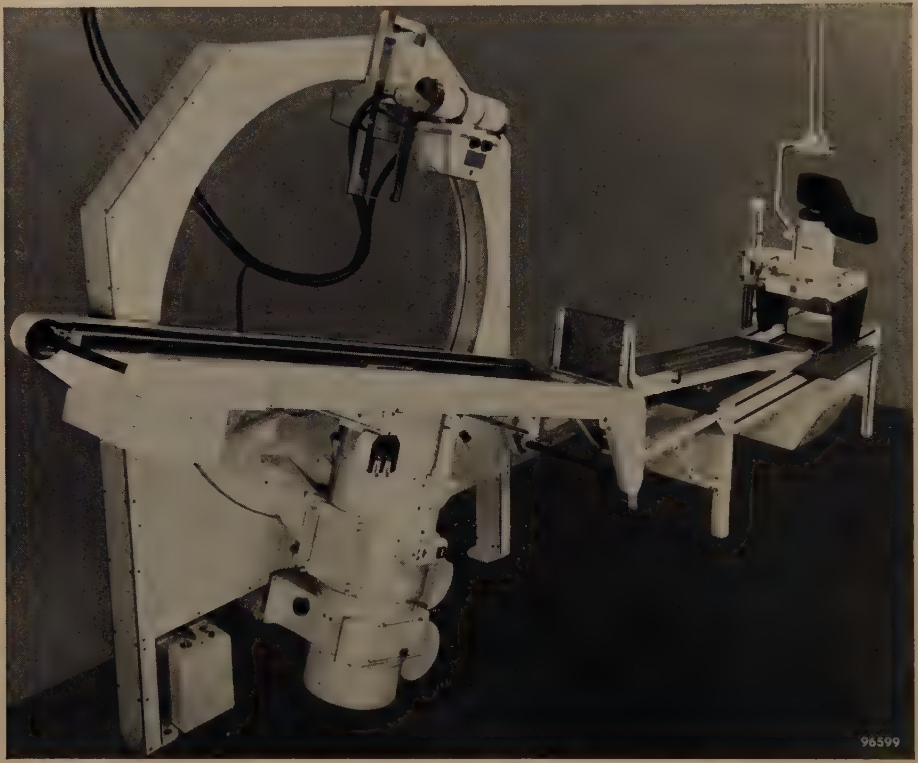


Fig. 13. Set-up for angiocardiography. For this examination a catheter is first introduced into or near the patient's heart via a vein. The introduction of the catheter is supervised by means of a 12.5 cm image intensifier, seen mounted above the catheterization table. The patient, with the catheter in position, is then conveyed to the "ring stand" by simply drawing the table top on which he is lying from the one stand to the other. The table top runs in U-channels with the aid of a chain drive.

rotation; otherwise it would be necessary to have a hole cut in the floor, which would be a nuisance as well as dangerous to the operating personnel. The table-top lies 15 cm away from the centre of rotation, so that the part of the patient to be filmed, e.g. the heart, lies practically at the centre of rotation. Apparatus not attached to the ring and used for lateral exposures (along the axis of the ring) does not therefore have to be moved when the ring is rotated. In order to position the patient with respect to the X-ray beam, the table-top itself can be moved in its own plane over 100 cm longitudinally and over 10 cm transversely. For this purpose the table-top slides on runner guides in the table frame, while the latter runs on rollers over two cross-bars fixed to the ring.

Special provision is made for angiocardiography. As a rule, this examination is preceded by a heart catheterization, which is carried out on a table designed for the purpose. To facilitate the conveyance of the patient from the catheterization table to the ring stand, we have designed the stand such that the table-top on which the patient lies can simply be drawn from the one table on to the other. *Fig. 13* shows how this is done, and also gives an impression of the apparatus involved in an angiocardiographic examination. In these examinations, which are now carried out in many parts of the world, cinefluorography has proved to be a very valuable technique. Full advantage can be taken here, too, of the feature of our cine-apparatus which allows two persons — the radiologist and cardiologist, or perhaps a trainee radiologist — to observe the X-ray image at the same time.

Summary. Since the image intensifier greatly reduces the dose of X-rays administered to the patient, its use for the purposes of cinefluorography is obviously indicated. The earlier described 5-inch image intensifier is already widely used in this way. A larger image intensifier has since been developed having a screen of 11 inch diameter, a reduction factor of 4.5 and a luminance intensification of approx. 100×, which makes it possible to examine cinematographically such large organs as the heart and lungs. In conjunction with this image intensifier, the construction and properties of which are discussed in this article, a special cinefluorographic apparatus has been designed, comprising a 35 mm mirror cine-camera (effective aperture ratio 1:0.83), an optical viewing system allowing two observers to watch the image during cinefluorography, and a luminance meter to regulate the average photographic density of the film or, if required, automatically keep it constant. The power supply for the X-ray tube contains a heat integrater, which safeguards the anode against overheating as a result of prolonged and severe loading. The cinefluorography apparatus, the X-ray tube and the examination table can be mounted on a "ring stand", which enables the patient to be tilted during the examination without shifting his position with respect to the X-ray beam. In conclusion the author discusses the application of the apparatus to angiocardiography.

MANUFACTURE OF FLUORESCENT LAMPS

Aging and final checks of fluorescent lamps, type "TL" E,
in the Philips Works at Roosendaal, Holland.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to Philips Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2.

2610: H. A. Klasens: Elektrolumineszenz von suspendierten Sulfidphosphoren (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick, 1958, pp. 247-262). (Electroluminescence of embedded sulphide phosphors; in German.)

Many sulphide phosphors, embedded in a suitable binder, fluoresce when subjected to an alternating electric field (electroluminescence: Destriau effect). An attempt is made to develop a picture of the mechanism of electroluminescence that admits a satisfactory explanation of the many observed phenomena.

2611: W. Hoogenstraaten: Der nicht-elektronische Energietransport in Phosphoren (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 285-305). (Non-electronic energy transport in phosphors; in German.)

Various mechanisms have been proposed to explain sensitization of fluorescence in inorganic phosphors. From a discussion of these mechanisms it follows that only two of them, viz. energy transfer by metastable excitons of the base lattice and resonance transfer between sensitizers (S) and activators (A), are not in contradiction with the qualitative behaviour of these phosphors. The quantum-mechanical theory of resonance transfer by dipole-dipole, dipole-quadrupole and exchange interaction is discussed in some detail. The phenomenological theories connected with the above transfer mechanisms are compared with the experimental results on the relative efficiencies of S- and A-fluorescence as a function of the concentrations of S and A. From this comparison it appears that resonance transfer from sensitizer to activator, either directly or via other sensitizers, is the most probable mechanism of sensitized fluorescence. Finally, a short account of host-sensitization is given.

2612: J. S. van Wieringen: Paramagnetic resonance in single crystals of SiC doped with N, P, B or Al (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 367-370).

Both n- and p-type SiC show paramagnetic resonance at liquid-nitrogen temperature, caused by electrons and holes respectively. The electron centre is located near one or more nitrogen nuclei and is isotropic. The hole centre shows anisotropic behaviour.

2613: P. Penning: Generation of imperfections by thermal stress (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 482-485).

Further considerations on the generation of dislocations during the growth of germanium crystals from the melt. (See also these Abstracts No. **R 338** and Philips tech. Rev. **19**, 357-364, 1957/58, No. 12.)

2614: J. A. Lely and F. A. Kröger: Optical properties of pure and doped SiC (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 514-524).

Absorption spectra of SiC, pure and doped with N or Al have been measured. Hexagonal SiC has an absorption edge at ~ 4000 Å, cubic SiC at 4400 Å. Incorporation of N in hexagonal SiC gives rise to absorption bands in the blue and red, causing a green transmission colour. Incorporation of Al gives rise to absorption bands in the green and red, causing a blue transmission colour. Various luminescence bands have been observed. In the infra-red, SiC shows strong absorption in bands from 6-13 μ. Analysis of the infra-red reflection spectrum shows that the wave-numbers of the transverse and longitudinal vibrations of the optical branch are $\nu_t = 800\ \mathrm{cm}^{-1}$, $\nu_l = 975\ \mathrm{cm}^{-1}$.

2615: J. A. Lely and F. A. Kröger: Electrical properties of hexogonal SiC doped with N, B or Al (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 525-533).

Measurements of the Hall effect and of conductivity as a function of temperature have been carried out for SiC doped with nitrogen, boron or aluminium. Analysis of the experimental data leads to the following results: 1) The depth of N donor levels below the conduction band $\varepsilon_D = 0.06\text{-}0.085$ eV. 2) The separation of Al and B acceptor levels from the valence band $\varepsilon_A = 0.275$ eV. 3) Lattice scattering causes the mobility to decrease with temperature according to $\mu_H = aT^{-b}$ with $b = 1.5\text{-}1.8$ for electrons and $b = 2.2\text{-}3.0$ for holes. 4) The effective mass ratio for electrons in the conduction band is approximately $(m^*/m)_n = 0.6$. An estimate based on the mobility ratio for electrons and holes leads to an effective mass ratio for holes in the valence band of $(m^*/m)_p \approx 1.2$.

2616: W. van Gool: Fluoreszenz und Photoleitfähigkeit in Zink-Kadmium-Sulfiden aktiviert mit Silber (Halbleiter und Phosphore, Internat. colloq. Garmisch-Partenkirchen 1956, edited by M. Schön and H. Welker, published by Vieweg & Sohn, Brunswick 1958, pp. 602-609). (Fluorescence and photoconductivity in zinc-cadmium sulphides activated with silver; in German.)

Some phosphors were made from CdS activated with Ag-Ga and Ag-Cl. These phosphors show two fluorescence bands at low temperatures, viz. 6200 Å and 7300 Å. The 6200 Å emission has only been found when the activator concentration (Ag) surpasses the coactivator concentration (Cl or Ga). By making a series of mixed crystals (Zn,Cd)S it can be shown that the 7300 Å emission corresponds to the 4500 Å emission in ZnS (sphalerite) and therefore to the normal silver centre (Ag^+ at a lattice site). The 6200 Å emission in CdS is connected with 3950 Å (sphalerite) or 3850 Å (wurtzite) in ZnS. The experimental conditions necessary to obtain the short-wave emission (Ag > Ga) indicate that the short-wave fluorescence centre is formed by interstitial silver, by a sulphur vacancy or by an association containing at least one of these defects. It is also clear that the inversion of the normal band model, as has been proposed by Lambe and Klick, may be possible for the short-wave centre (6200 Å in CdS, 3950 Å in ZnS); there are no indications, however, that the band model of the normal silver centre (7300 Å in CdS, 4500 Å in ZnS) ought to be changed.

2617: P. Penning: Coefficient for self-diffusion determined from the rate of precipitation of Cu in Ge (Phys. Rev. **110**, 586-587, 1958, No. 2).

From data published by Tweet on the rate of copper precipitation in Ge during annealing, and its dependence on the dislocation density, it is shown that the coefficient of self-diffusion of germanium can be derived. The results agree closely with measurements made with radio-germanium, indicating firstly the validity of the vacancy-mechanism assumption, and secondly that etch-pit counts give an accurate measure of the density of dislocations that absorb vacancies.

2618: J. S. C. Wessels: Studies on photosynthetic phosphorylation, II. Photosynthetic phosphorylation under aerobic conditions (Biochim. biophys. Acta **29**, 113-123, 1958, No. 1).

The aerobic photochemical esterification of inorganic phosphate to adenosine triphosphate has been investigated. Evidence is presented in support of the conclusion that under aerobic conditions, in contrast to anaerobic phosphorylation, vitamin K_3 and flavin mononucleotide are interchangeable and are not involved in separate pathways for photosynthetic phosphorylation. A tentative scheme for the generation of adenosine triphosphate in chloroplasts is given and discussed in relation to the effect of various inhibitors on phosphorylation. (See also these Abstracts No. **2509**.)

2619: R. Dijkstra and J. de Jonge: The chemical effect of light on sodium p-methoxybenzenediazosulphonate (Rec. Trav. chim. Pays-Bas **77**, 538-554, 1958, No. 6).

It is deduced from kinetic measurements that irradiation of an aqueous solution of p-methoxybenzenediazosulphonate with ultra-violet light causes a dissociation of the sulphonate ion to form a p-methoxybenzenediazonium ion and a sulphite ion. The ions produced photochemically slowly recombine in the dark to form back the original sulphonate ion. The reactions may be represented by the scheme:

$$CH_3O.C_6H_4.N{=}N{-}SO_3^{(-)} \underset{\text{(light)}}{\overset{\text{(dark)}}{\leftrightarrows}} CH_3O.C_6H_4.N_2^{(+)} + SO_3^{(--)}.$$

The occurence of a labile or cis-diazosulphonate can almost certainly be excluded.